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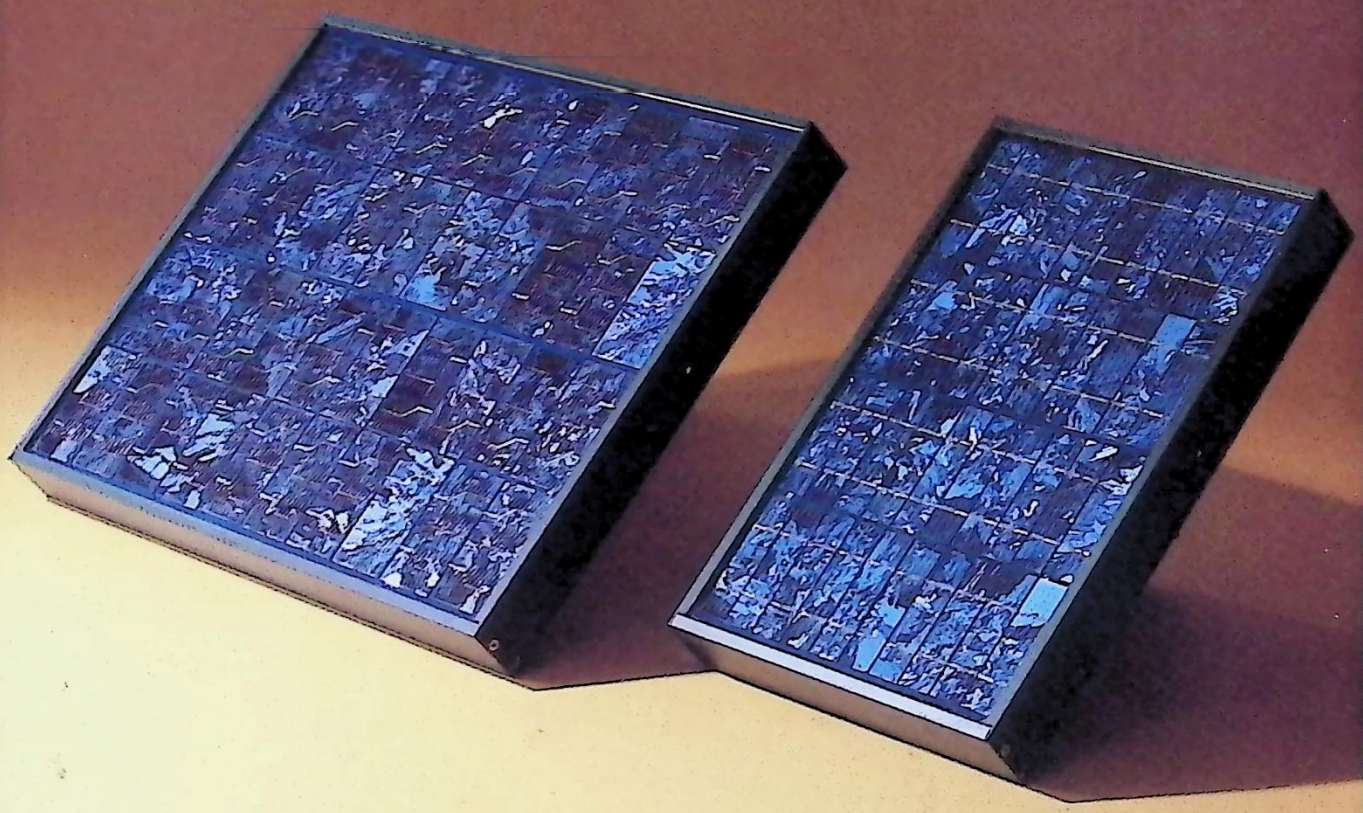
THE SOLAREX GUIDE TO SOLAR ELECTRICITY



EDITED BY ED ROBERTON
BY THE TECHNICAL STAFF OF SOLAREX CORP.

THE SOLAREX GUIDE TO SOLAR ELECTRICITY

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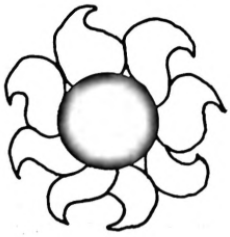
Cover photo of two high-density Solarex panels using polycrystalline cells.

Preface



The idea of being able to get useful energy from the sun has been a dream of scientists for centuries. The sun is an inexhaustible source of energy, and sunlight is available all over the earth. What is needed to utilize the energy in sunlight is some efficient way to convert the radiant energy in sunlight into some form of energy that is easier to use, such as electrical energy. The silicon voltaic cell, or solar cell as it is commonly called, is just such a device.

The photovoltaic effect, where electricity is produced when certain materials are illuminated, is not new. It was first noted by E. Becqueral in 1839. Thus the photovoltaic cell is probably the first solid-state electronic device ever invented. It is certainly much older than the radio crystal detector which has often been called the first solid-state electronic device.

The utilization of the photovoltaic cell as an energy source has been very slow, primarily because of the abundance of hydrocarbon fuels such as coal, oil, and natural gas. The first practical use of the photovoltaic effect was in selenium cells that were, and still are, being used to measure light levels. A typical example is the light meter used in photography.

The first significant use of photovoltaic cells to produce electrical energy was in the space program. Satellites need a source of electrical energy that will last for a long time without any attention. All conventional batteries will run down after a

period of use. The solar cell, however, will continue to deliver electric power as long as sunlight is available.

In recent years the development of solar cells has accelerated rapidly. This is due in part to the realization that our supply of hydrocarbon fuels, while large, is not inexhaustible. Another factor that has contributed to the development of solar power sources is the increasing concern about air and water pollution resulting from the burning of hydrocarbon fuels, and a possible hazard connected with the use of nuclear fuels.

Whereas the cost of conventional fuels has skyrocketed in recent years, the cost of solar cells has been declining steadily. The U.S. Department of Energy has a stated goal of reducing the cost of solar cells to $0.50 per peak watt by 1986. Even if this goal is not completely realized, the program will make the solar cell competitive with many other energy sources.

This book is for anyone interested in solar cells as a source of energy for any requirement, large or small. Chapters 1-3 are background material for readers who are not familiar with either solar energy or the photovoltaic effect. Chapters 4-6 deal with practical solar cells, their use and typical applications. A separate chapter describing a few solar cell projects is for the experimenter who wishes to build either demonstration or practical energy sources. Chapter 8 covers commercially available accessories that make installation and use of a solar electric system easier.

Chapter 9 deals with the use of solar cells as light sensors rather than as power sources. In Chapter 10 you will find a summary of current research in photovoltaics and the most recent technological developments in the field. Chapter 11 provides advice on planning, sizing, and installing your own solar-electric household system. A glossary is included for those not familiar with the terminology that is springing up in connection with the application of solar electricity.

Technical Staff
Solarex Corporation

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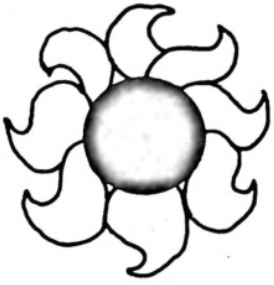

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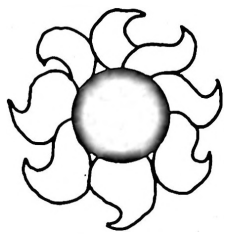
Introduction



When solar cells were invented in the early 1950's, their use for terrestrial applications was considered. At that time the cost of electricity and energy producing means was still declining, and the newly-invented solar electricity was not even in the ballpark. It might have been forgotten if the space program had not come about.

What was expensive for earth use—when oil, gas, batteries, etc. were abundant—was inexpensive for space use. The U.S. space program then brought solar cells out of the laboratory into limited production, and they became the power source for the satellites. Because of the required high reliability and the premium on size and weight, space solar cells became rather expensive and efficiency became the key word.

Solar cell efficiency improved slowly for 10 years until an abrupt improvement occurred in 1972 and a high efficiency solar cell was developed.

Although solar cells proved to be an extremely reliable and simple source of electricity for space use, due to their cost, only a small number of space reject cells were used for terrestrial applications as late as 1972. The primary reason was that solar cell technology was not applied to production of

inexpensive solar cells for terrestrial use. In 1972 it was considered that the cost of solar electricity was over $100/watt compared to about $1/watt or less for conventional electricity.

Dr. Joseph Lindmayer, known for his work in solid-state physics and who invented the high-efficiency solar cell, and Dr. Peter Varadi, who had broad experience in materials technology and business administration, recognized that solar electricity was feasible and would be one of the most important energy sources of the future. At that time no serious effort was made by any company to develop and mass produce solar cells and generators for terrestrial use only.

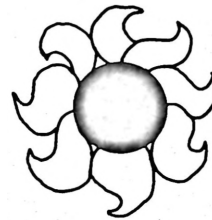
With this in mind, Solarex Corporation was formed in early 1973 with the purpose of devoting its entire effort to solar energy and to advancing the state of art by progressive research and development and manufacturing.

Solarex Corporation is a leader in the development of terrestrial solar cells to convert light to electricity. It has total manufacturing capability to produce efficient solar cells and to integrate them into solar panels. Solarex builds standard solar panels (Unipanels®) and assembles these building blocks into larger solar-electric generators.

Solarex is equipped to develop and custom-design any type of solar-electric cell, panel or system. Solarex products will always incorporate the most advanced concepts in solar-electric conversion. In 1973 Solarex developed its terrestrial solar cell which, even by its appearance, can be easily distinguished from other solar cells.

Solarex is located in the suburbs of Washington, D.C. (20 miles from the White House) in a modern building, selected and designed to provide a research and development and production facility as well as a capability for undisturbed environmental testing of solar conversion equipment. Engineering data obtained from this test facility is being used in the design of solar-electric systems.

Chapter 1
A Little About Sunlight



Sunlight is one of those things that most of us take for granted. We know in a vague sort of way that we can get energy from the sun, but that's about the extent of our knowledge. The fact is that all energy on earth originally came from the sun. All of our hydrocarbon fuels such as coal, oil, and natural gas, were originally produced by the action of sunlight on vegetation.

In order to understand how we can use solar cells to get electrical energy from sunlight, we should know a little bit about the nature of light and the units that are used to measure it. Light is a form of electromagnetic energy—just like a radio or a television signal. The only difference is that the wavelength of light is very much shorter than that of radio waves. The color of light is determined by its wavelength. The longest light waves that we can detect visually are red in color and the shortest are violet.

ENERGY, POWER & POWER DENSITY

How do we measure the energy that reaches the earth from the sun? What units do we use to express it? From elementary physics we learn that energy is the capacity to do work. It is measured in such units as the gram-calorie, the

Table 1-1. Coversion Factors For Energy

MULTIPLY → BY / TO GET ↓	WATT-HOURS	KILOWATT-HOURS	JOULES (WATT-SECONDS)	KILOGRAM-CALORIES
WATT-HOURS	1	10^3	2.778×10^{-4}	1.163
KILOWATT-HOURS	10^{-3}	1	2.778×10^{-7}	1.163×10^{-3}
JOULES (WATT-SECONDS)	3.6×10^3	3.6×10^6	1	4.187×10^3
KILOGRAM-CALORIES	8.599×10^{-1}	8.599×10^2	2.388×10^{-5}	1

joule, or the kilowatt-hour. The ordinary household electricity meter measures electrical energy in kilowatt-hours.

An inconceivable amount of energy is radiated by the sun. Only a very small fraction of this energy—about one-half of one billionth—ever reaches the earth. This small fraction, however, is still a tremendous amount of energy. It has been estimated that every year about 745 quadrillion kilowatt-hours of energy reach the earth from the sun. It is understandable why scientists have sought for years for ways to harness this energy.

Although energy is the more fundamental concept, in practical applications we are usually more interested in *power*, which is the rate at which energy is generated or used. Power is measured in watts or kilowatts.

The amount of power that we can get from any device that harnesses sunlight depends on the amount of sunlight that it intercepts. A device that has a larger area will intercept more power from sunlight than a smaller device. For this reason we often speak of sunlight in terms of *power density*. Power density is simply the amount of power in a given area. We usually express power density in terms of milliwatts per square centimeter (mW/cm^2) or kilowatts per square meter (kW/m^2).

Historically, most of the measurements of the amount of sunlight reaching the various parts of the earth have been made by people interested in forecasting weather. Not surprisingly, they have their own unit of measurement for the purpose. It is the *langley*. One langley is equal to 11.62

Table 1-2. Conversion Factors For Power

MULTIPLY → / BY / TO GET ↓	MILLIWATTS	WATTS	KILOWATTS
MILLIWATTS	1	10^{3}	10^{6}
WATTS	10^{-3}	1	10^{3}
KILOWATTS	10^{-6}	10^{-3}	1

watt-hours per square meter. In Chapter 5, we will show how to use a more convenient unit, the number of *peak sun hours*.

In the literature about solar energy you will find these and other units used to measure energy, power, and power density. Tables 1-1, 1-2, and 1-3 show how to convert from one such unit to another. Using a small pocket calculator the conversion is very easy.

HOW MUCH ENERGY FROM SUNLIGHT?

The power density of sunlight reaching the outside of the earth's atmosphere is about 136 mW/cm^2. About one-third of

Table 1-3. Conversion Factors For Power Density

MULTIPLY → / BY / TO GET ↓	mW/cm^2	W/m^2	kW/m^2
mW/cm^2	1	10^{-1}	10^{2}
W/m^2	10	1	10^{3}
kW/m^2	10^{-2}	10^{-3}	1

this energy is scattered while passing through the earth's atmosphere. Thus on a clear day at noontime the power density of sunlight is about 100 mW/cm^2. This amounts to about 1 kW/m^2 or in more familiar units about 1 kilowatt per square yard.

Of course the actual power density at the surface of the earth depends on many factors. The figures quoted above are for a clear day at noontime. Early in the morning and late in the afternoon, when the sun is lower in the sky, the amount of energy received is lower, as it is on cloudy or rainy days.

The actual amount of power that we can recover from sunlight depends not only on the amount of sunlight that reaches a given area in a year, but also on the efficiency of our energy conversion device. These factors will be treated in detail in Chapter 5. We can, however, get some idea of the amount of energy that we are talking about from the fact the solar energy that is intercepted by a small tennis court would supply the energy needs of an average household. The solar energy that reaches less than one percent of the Sahara desert is more than all of the electrical energy used by all of the nations of the world.

THE UNITS OF WAVELENGTH

We mentioned earlier that light is actually a form of electromagnetic energy. The wavelength of visible light is very short as compared to that of a radio wave and therefore the usual units of measurement of wavelength, such as the

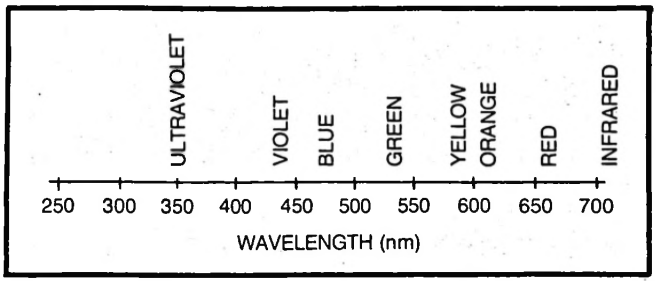


Fig. 1-1. Color of light as a function of wavelength. Units are in nanometers.

Table 1-4. Conversion Factors for Wavelengths

MULTIPLY BY → / TO GET ↓	MICRONS	ANGSTROMS	METERS	NANOMETERS
MICRONS	1	10^{-4}	10^{6}	10^{-3}
ANGSTROMS	10^{4}	1	10^{10}	10
METERS	10^{-6}	10^{-10}	1	10^{-9}
NANOMETERS	10^{3}	10^{-1}	10^{9}	1

meter, are inconveniently large. A suitable unit for the measurement of the wavelength of light is the *nanometer*. A nanometer is equal to a billionth of a meter, or in mathematical language, 10^{-9} meter. In some of the older literature on light the nanometer is called a millimicron. A micron is a millionth of a meter. Another name for the micron is micrometer.

Figure 1-1 shows the relationship between the wavelength and its color. Table 1-4 can be used to convert between nanometers and other units that are sometimes used

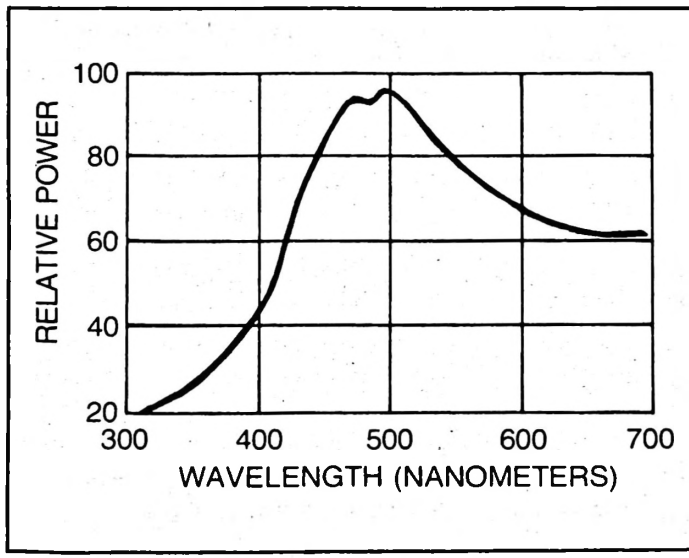


Fig. 1-2. Spectral distribution of daylight. Units are in nanometers.

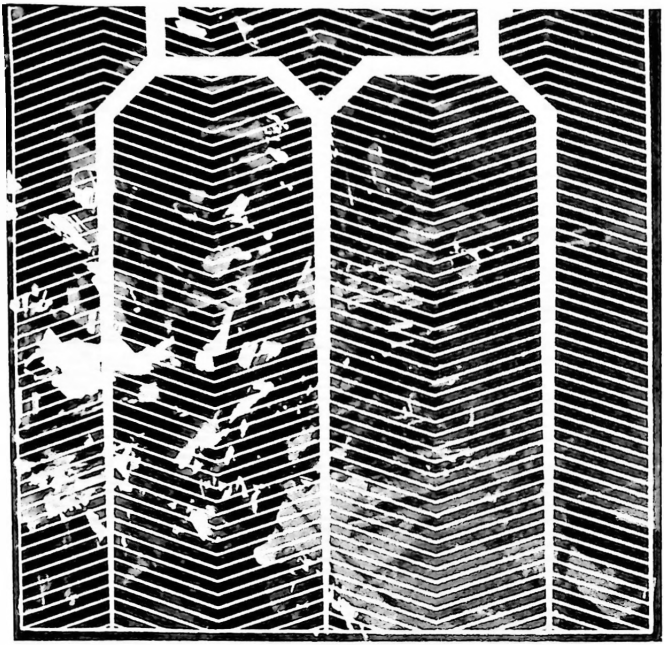


Fig. 1-3. The new high-efficiency solar cell invented and manufactured by Solarex Corporation is made of inexpensive semicrystalline silicon. Its square shape reduces nonproductive areas in photovoltaic panel. Together these advantages mean significant savings in the cost of solar electricity.

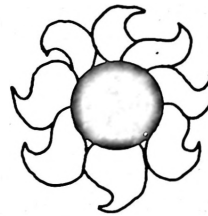
to express the wavelength of light. Figure 1-2 shows the spectral distribution, that is, the amount of each color in ordinary daylight.

For many years, the nature of light was a subject of hot debate by physicists. At the time of Sir Isaac Newton, about the year 1666, light was considered to consist of tiny particles or corpuscles. Later, in 1865, Maxwell showed that light was wavelike in nature. Still later, in 1905, Albert Einstein showed that light was corpuscular in nature. Actually, there is evidence to support both theories. To the layman, this situation is apt to be confusing, but the easy approach is to use whichever point of view works best in a particular situation.

In most applications the wave theory of light will work

perfectly well. We do not need to get involved in particle physics. The exception is when we try to understand what goes on inside a solar cell. Here, we can best describe what happens by considering light to consist of small bundles of energy called *photons*. The photon is the smallest particle of light that can exist physically.

Chapter 2
The Photovoltaic Effect



The silicon solar cell is actually a *photovoltaic* cell. The word photovoltaic means the direct conversion of light into electricity. The photovoltaic cell is a semiconductor device. In order to understand how it works we will first review the basic principles of semiconductors.

SEMICONDUCTORS

A semiconductor material, such as silicon or germanium, is a material that is classified somewhere between being a good conductor and being a good insulator. Silicon is one of the most commonly used semiconductors. There is not likely to be a shortage of it because about twenty-five percent of the earth's crust is made up of silicon. Silicon usually occurs as a compound such as the silicon dioxide that makes up ordinary sand. It can be reduced to a pure metallic form by a reduction process.

After silicon has been refined and purified it can be formed into a crystalline structure. Each atom in the outer ring of the silicon atom has a definite place in the crystal structure. Thus there are not any free electrons in a pure silicon crystal. As a result it is a rather poor conductor of electricity because a

lot of force is required to draw the electrons out of their places in the crystal lattice.

To make silicon that is useful in electronic devices such as diodes, transistors, or solar cells, the material is changed by adding minute amounts of other elements. This process is called *doping* of the silicon.

When a very small amount of phosphorus is added to silicon while the crystal is being formed, there will be some free electrons in the material which do not have definite places in the crystal structure. These free electrons can move about easily and are called negative, or N-type charge carriers. Silicon that is doped with phosphorus is called N-type silicon.

If, instead of adding phosphorus, we add boron to the silicon while the crystal is being formed, we have a completely different situation. There are no free electrons. In fact there are places in the crystal where there would be electrons in pure silicon. These voids in the crystal are called *holes*. These holes can move easily from one place in the crystal structure to another. What really happens is that one of the electrons in the crystal structure will fill one of the holes, leaving another hole in the place that it came from. Inasmuch as the holes actually move by electrons filling them, each hole will have a positive charge that is equal and opposite to the negative charge of an electron. Silicon doped with boron is called P-type, or positive type silicon.

Figure 2-1 shows the extra holes in P-type material and the extra electrons in N-type material. As we stated earlier, the holes have a positive charge and the electrons have a negative charge. Note, however, that this does not mean that the material itself has an electric charge. Although the electrons and holes have electric charges, there are an equal number of positive and negative charges in the nucleus of the atoms of the material that are not free to move around in the material. These charges cancel out the charges of the holes and electrons so that the material itself is electrically neutral. Figure 2-2 shows how P-type and N-type silicon can be combined to form a semiconductor junction.

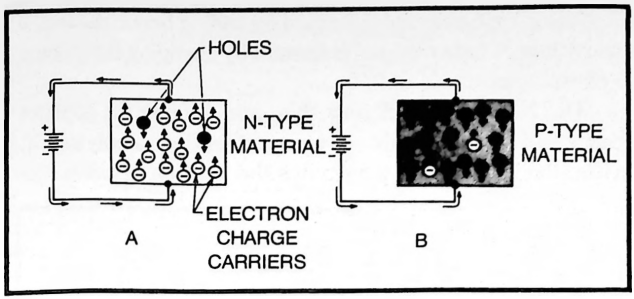


Fig. 2-1. Current flow in semiconductor materials. (A) N-type material. Majority of current flow is electron movement. (B) P-type material. Majority of current flow is hole movement.

To understand how light interacts with a semiconductor material, we will make use of both the corpuscular and wave theories of light. First let's think of light as consisting of particles called photons. When a photon penetrates a semiconductor material such as silicon, it will force an electron out of its place in the crystal structure. This forms what we call a *hole-electron* pair. The electron has a negative charge, and the hole that it leaves will have a positive charge.

If we don't make any other provisions, this hole-electron pair will have a very short life indeed. In a period of about a millionth of a second, the electron will move right back into the hole in the crystal that it came from. This process is called *recombination* of the hole and the electron.

The depth to which a photon will penetrate the silicon depends on its energy. This is most easily explained by going back to the wave theory of light. Light of a longer wavelength will produce photons having more energy. In practical terms this means that the degree to which light will penetrate into the silicon depends on its wavelength. In general, light having a longer wavelength will penetrate more deeply into the silicon.

THE PHOTOVOLTAIC CELL

Figure 2-3 shows a sketch of a photovoltaic cell. The base material at the right of the figure is made of P-type silicon.

After the P-type material is formed by adding boron doping, a thin layer of N-type material is formed by changing the doping to phosphorus.

The N-type layer is very thin, and although it appears opaque to the eye, sunlight will penetrate rather deeply into it. In fact, the light actually penetrates the junction between the

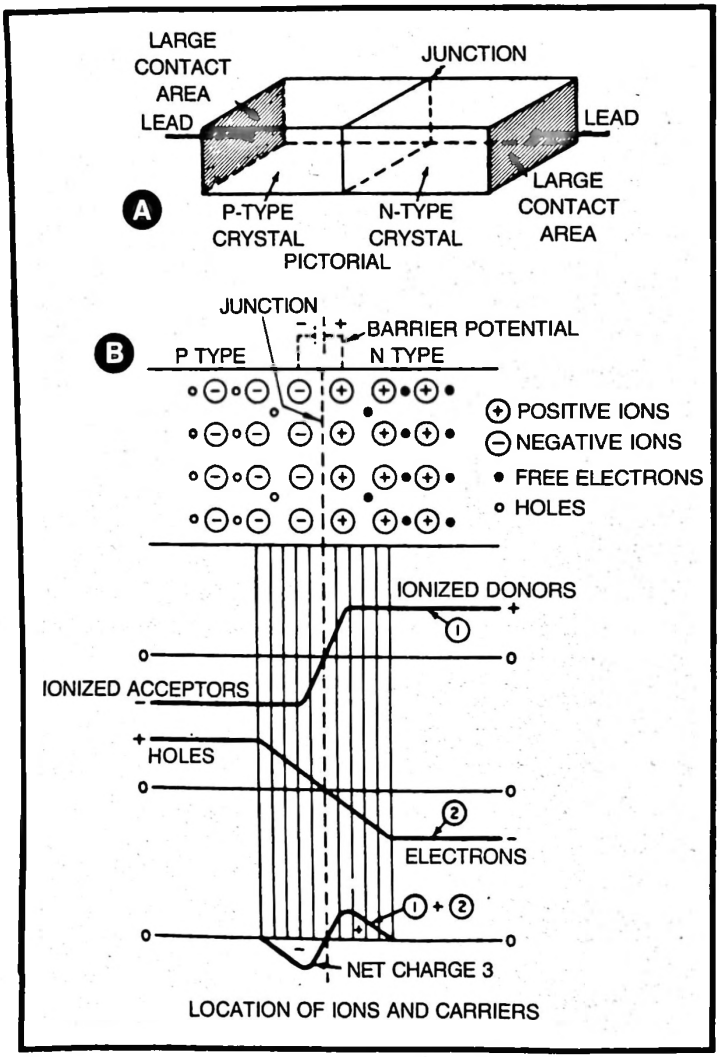


Fig. 2-2. Formation of a PN junction.

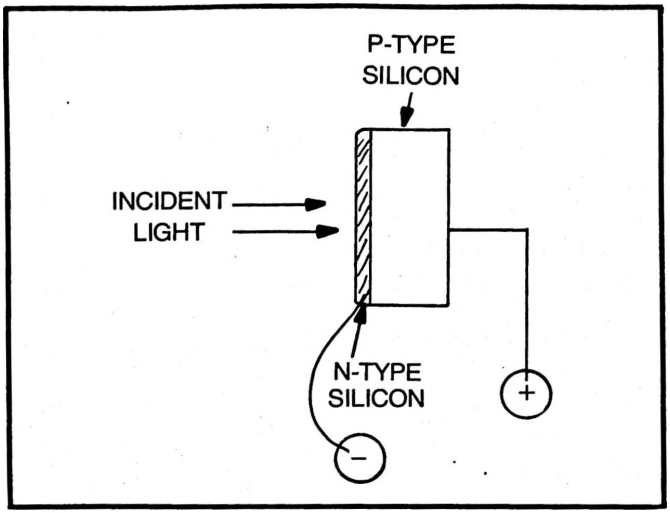


Fig. 2-3. Elementary silicon photovoltaic cell.

N-type and P-type material. This is where the hole-electron pairs that we talked about earlier are formed. The electric field that exists at the junction will prevent the holes and electrons from recombining, with the result that we can now use the

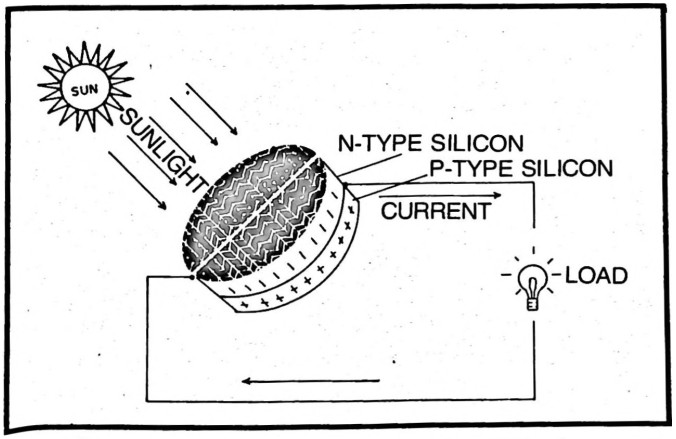


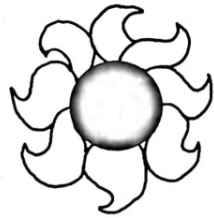
Fig. 2-4. Solar cell connected to a load.

device as a source of energy. The N-type material will be the negative pole and the P-type material will be the positive pole of what amounts to a little electric generator that gets its energy from sunlight.

Figure 2-4 shows how a solar cell is connected to a load. The photovoltaic action of the sunlight on the solar cell will cause current to flow through the load. In the following chapter we will see how the amount of electricity produced by the cell is related to the amount of light, and how the load can be adjusted to get the maximum amount of energy from the cell.

Chapter 3

The Silicon Solar Cell



In the preceding chapter we saw how the photovoltaic effect in silicon can be used to generate electricity directly from sunlight. In this chapter we will take a detailed look at the electrical characteristics of a solar cell utilizing this effect. In particular we will see how the voltage and current produced by a solar cell vary with different load conditions and how the output varies with the amount of available light.

CURRENT VERSUS VOLTAGE CURVES

Whenever we use any source of electric energy, it is helpful to know just how the terminal voltage and current will change as the load is varied. The solar cell is a nonlinear device, so it isn't convenient to try to use a mathematical expression for this characteristic. Instead, we will use a family of easily understood curves on a graph.

One way that we can plot such a set of curves is to connect the solar cell in the circuit shown in Fig. 3-1 and vary the load resistance over a wide range while noting the values of voltage and current indicated on the meters in the circuit.

Suppose that we have a silicon solar cell connected in the circuit of Fig. 3-1 and it is subjected to an amount of light

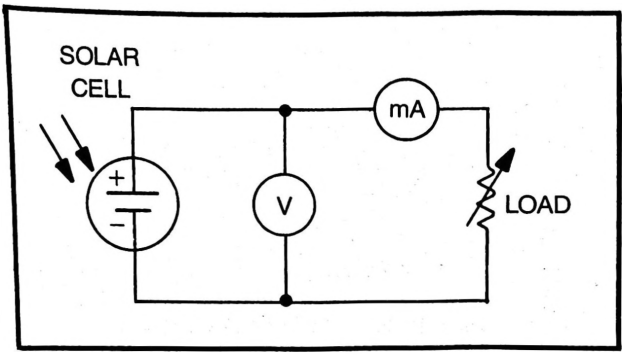


Fig. 3-1. Circuit for plotting voltage-current curves.

approximately equal to the maximum value of sunlight at the surface of the earth—about 100 mW/cm^2. To start, suppose that we make the load resistance so high that for all practical purposes we can consider it to be an open circuit. Naturally, the current indicated on the milliammeter will be zero because no current can flow into an open circuit. With the silicon cell, the terminal voltage under this condition will be about 0.570 volts. This point is labeled *A* in Fig. 3-2. It is also labeled as Voc—the open-circuit voltage.

Now let us assume that we slowly decrease the load resistance. We will find that the terminal voltage drops very slowly, but that the current increases rather rapidly. This continues until we reach point *B* on the curve. At this point the voltage has dropped to about 0.45 volts and the current has increased to about 780 milliamperes. The shape of the curve changes rather drastically at this point, which is often referred to as the knee of the curve.

If we continue to decrease the load resistance, the voltage will continue to drop, but the current will remain nearly constant. When the load resistance reaches zero, the voltage will, of course, be zero because we can't have a voltage across a short circuit. This is labeled as point *C* on the curve. It is also labeled as Isc because it shows the short-circuit current of the cell.

MAXIMUM POWER

Now that we have a curve that shows the voltage-current characteristic of the solar cell, the question naturally arises as to just where on the curve we should try to operate the cell. We can, of course, establish the operating point by properly adjusting the load resistance. In fact, the load resistance that will cause the cell to operate at any point on the curve can be found by dividing the voltage by the current at that particular point on the curve.

In most practical applications we will want to operate the cell in such a way that it will deliver the maximum amount of power to the load. Figure 3-3 shows the same graph that we showed in Fig. 3-2, but now we have added another curve.

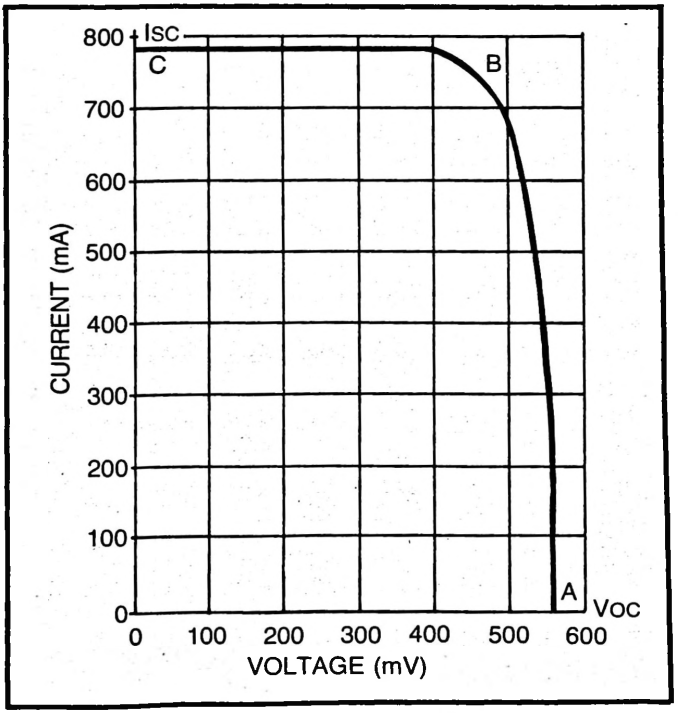


Fig. 3-2. Voltage-current curve for a solar cell.

The dashed line and the scale at the right of the graph show the amount of power that the cell will deliver to the load when it is operated at any point on the curve. Intuitively, we know that can't get much power into either an open or a short circuit. We expect that amount of power that we can get to be maximum when we operate the cell somewhere between these two extremes.

Interestingly, the power that is delivered to the load will be maximum when we operate the cell at about the knee in the characteristic curve.

OUTPUT POWER VERSUS SUNLIGHT

The curves of Fig. 3-2 and 3-3 were obtained when the cell was subjected to the maximum value of sunlight. Although this is an ideal operating condition, maximum sunlight is not always available, so we must know how the cell will behave when the level of light is reduced.

Figure 3-4 shows a family of curves similar to those of Figs. 3-2 and 3-3, but for different values of light reaching the solar cell. The top curve of Fig. 3-4 is almost exactly the same curve that we studied in Figs. 3-2 and 3-3. The next curve on the graph represents what happens when the power from the sunlight is cut in half. Note that to the left of the knee the curve has the same shape as the curve above it and the one below it. In this portion of the operating range the terminal voltage is not significantly affected by the amount of light. It is the current that changes. Inasmuch as the voltage doesn't change very much, power will be proportional to current, and the current will decrease linearly with the amount of light reaching the cell.

To the left of the knees of the curves in Fig. 3-4 we see that the terminal voltage does to some extent depend on the amount of light. At very low levels, about 8% of the maximum sun level, the voltage decreases noticeably. Nevertheless, over most of the operating range, the current from the cell changes much more than the voltage when the light level changes.

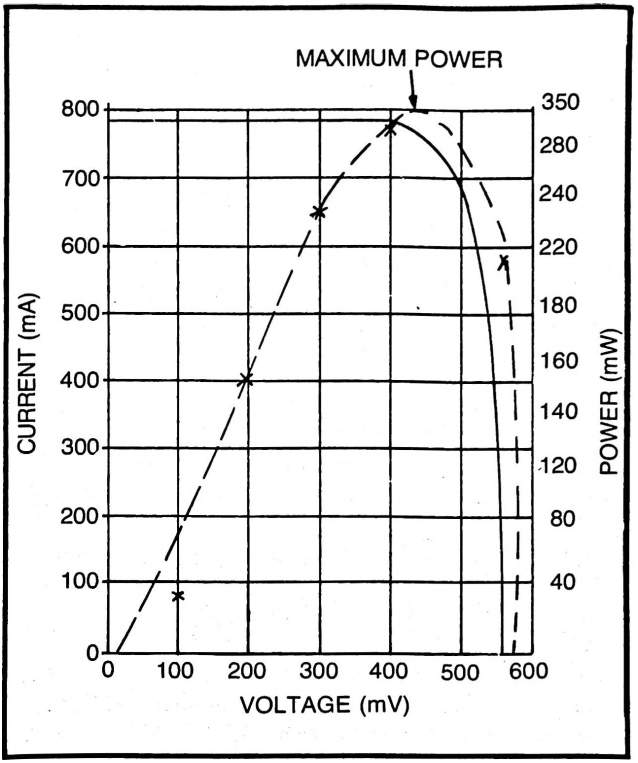


Fig. 3-3. Voltage-current curve of solar cell with power plotted also.

This has an important implication in many practical applications of solar cells. The fact that the curves have the same shape except at very low light levels means that we will get nearly the maximum amount of power at all except the lowest light levels if we operate the cell at the knee of the curve. Thus, in many applications, there is no need to change the load as the amount of light varies.

We can also draw a few more conclusions from the family of curves shown in Fig. 3-4. In the first place, we note that except at low light levels the voltage from the cell doesn't

change very much with the amount of light. From this we might guess that the voltage from a cell wouldn't change very much as the cell was made larger or smaller. This is indeed true. The voltage produced by a solar cell is roughly 0.45 volts regardless of the area of the cell.

We also note that the current produced by the cell varies greatly with the amount of light reaching the cell. This would lead us to suspect that a cell with a larger area would produce more current. This suspicion is correct. The amount of current from a solar cell increases linearly with both the area and the amount of light.

THE SOLAR CELL AS AN ENERGY SOURCE

The voltage-current curves of a solar cell, such as those shown in Fig. 3-4, completely describe its electrical behavior. From these curves we see that the solar cell is not much like other voltage sources with which we may be familiar. A battery, for example, behaves very much like a constant voltage source except at very high load currents. The current from a battery will increase as the load resistance decreases, but the terminal voltage will not change very much until the load current becomes very high. We can't operate a battery into a short circuit. The current would become excessive and the battery would be destroyed.

By contrast, the solar cell acts very much like a constant current source over most of its operating range. Even if the load resistance were to become very low, the current would not become excessive. This feature makes the solar cell ideal for unattended operation. We don't have to keep an eye on the load current because the cell will not destroy itself.

SPECTRAL RESPONSE

Another important characteristic of any photoelectric device is what is called its spectral response. This is its relative response to light of different wavelengths. Figure 3-5 shows the spectral response of a silicon solar cell. The horizontal axis

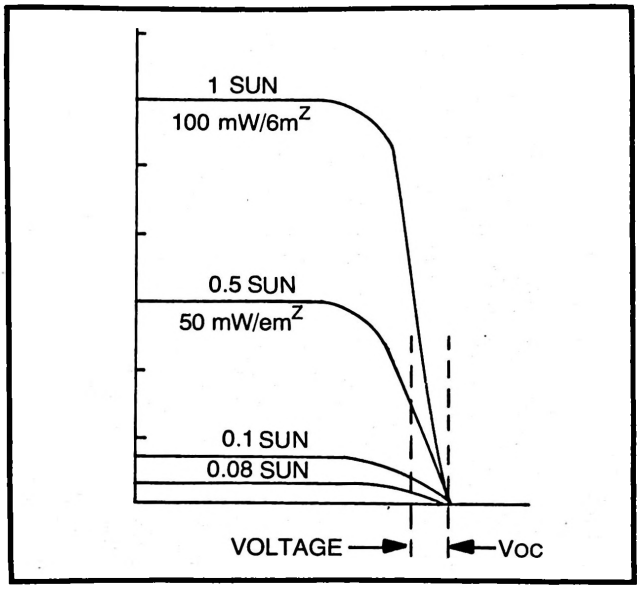


Fig. 3-4. Solar cell output of different amounts of sunlight.

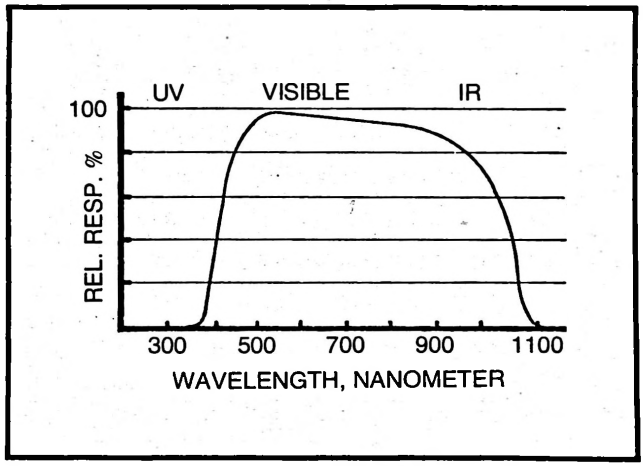


Fig. 3-5. Spectral response of silicon photovoltaic cell.

shows the wavelength of the incident light and vertical axis shows the response.

Of course, we don't have any control over the wavelength of sunlight, but the curves show that the silicon solar cell has a relatively high response to a broad range of wavelengths ranging from the ultraviolet, through the visible portion of the spectrum, into the infrared. This means that the solar cell will produce electrical energy under a wide variety of conditions. It will respond well on cloudy days and will produce a useable output when illuminated by ordinary incandescent or flourescent lamps. This makes the silicon solar cell useful in photoelectric applications other than generating power from sunlight.

ENERGY CONVERSION EFFICIENCY

So far, we have talked about the amount of power in the sunlight that might reach a solar cell and about the electrical power that we can get out of the cell. We haven't said anything about the energy conversion efficiency. This is the ratio of the power that we can get out of a cell to the power in the sunlight that it receives.

It turns out that there is a theoretical limit to the maximum efficiency that can be obtained with a silicon solar cell of the type that we have been discussing. This theoretical limit of energy conversion efficiency turns out to be about twenty-five percent. This sounds like a very low figure until we realize that energy conversion efficiencies in this order are common. The ordinary automobile engine has an energy converison efficiency of only about twenty percent.

There are many practical considerations that determine just how efficient a given solar cell will be. One of the connections to the cell is made to the thin layer of N-type material on the face of the cell. If the metallic conductors used to make this connection are too large, they will block the sunlight from part of the cell. If the metallic conductors are made too small, they will have a high electrical resistance.

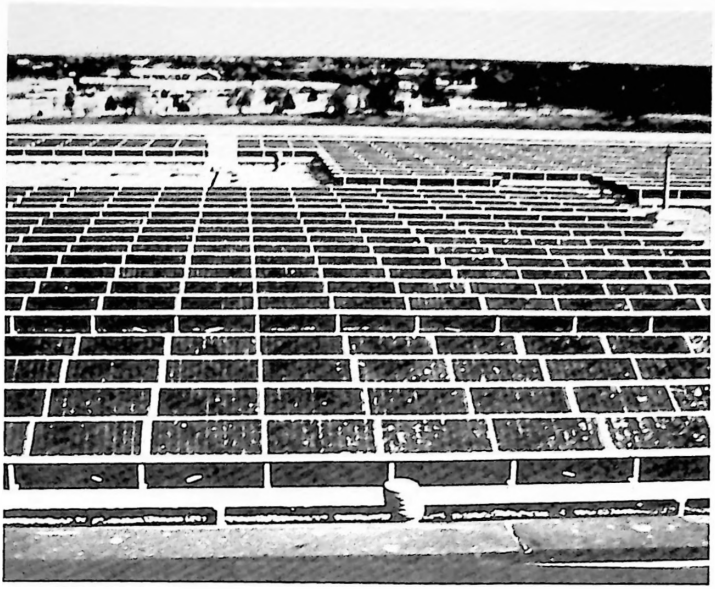
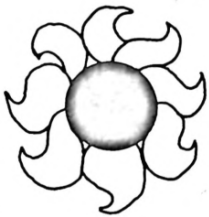


Fig. 3-6. This extensive photovoltaic panel array produces 105 kW to meet the power needs of the Oklahoma Center for Science and the Arts in Oklahoma City.

When individual cells are combined into an array, their geometrical configuration will determine whether or not they make maximum use of the available area. The efficiencies that can be expected from practical solar cells will be discussed in the following chapter.

Chapter 4

Practical Solar Electric Generators



The basic element of a solar electric generator is the silicon solar cell. Figure 4-1 shows the stages in the process by which a solar cell is made from the original brick of semi-crystalline silicon—a very abundant mineral—through its division into ingots, then thin wafers, and finally, a usable photovoltaic material.

Solar cells are available in many sizes and shapes. Among the most popular is the rectangular cell because it permits many cells to be mounted together in panels, making the most efficient use of the panel's area. Cells also are commonly made in circular, semicircular, and crescent shapes.

When the application calls for a considerable amount of power, more than a single cell must be used in the generator. For such applications many cells are combined into assemblies called solar panels. When still more power is required, several panels can be combined into large arrays.

At the other extreme, when only a very small amount of power is required, several very small cells are combined into assemblies called Microgenerators® which can be used to supply power to small electronic devices such as watches, calculators, etc.

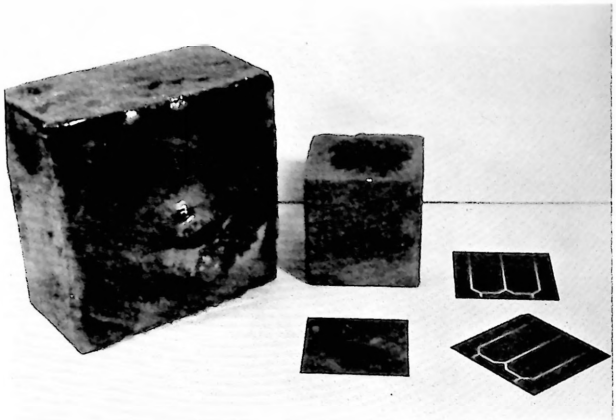


Fig. 4-1. The manufacturing process for solar cells starts with a large brick of semicrystalline silicon, from which are cut ingots, then wafers, leading to a finished cell.

Figure 4-2 shows a sketch of a solar cell. The manufacturing process starts out with nearly one hundred percent pure silicon material. To form the bottom layer of the cell, boron is added in minute amounts while the silicon crystal is being formed. This makes the bottom layer of the cell P-type material. After the P-type layer has been formed, phosphorus is added to form the thin layer of N-type material, thus forming the PN junction which is essential for the operation of the cell. Metallic connections are provided to both the P-type and N-type layers.

CONSTRUCTION & EFFICIENCY

We noted earlier that the theoretical limit of efficiency of a photovoltaic cell is in the order of twenty-five percent. The actual efficiency that can be obtained in practice is somewhat lower than the theoretical limit and depends to a great extent on the manufacturing process and materials used to make the cell.

The efficiency of the cell is quite important because the higher the efficiency, the fewer cells will be required in a given

application. For example, a three-inch circular cell with an efficiency of twelve percent will provide 0.547 watts at 1.2 amperes. A similar three-inch cell with an efficiency of ten percent would only provide a power of 0.456 watts at 1.0 amperes.

The efficiency of a solar cell is the ratio of the power output to the power input. It can be expressed by the equation:

$$\text{Efficiency Percentage} = \frac{\text{Power Output}}{\text{Power Input}}$$

Many factors influence the efficiency of a practical solar cell. In order for the cell to be able to supply power to an external circuit we must have metallic connections to both the P-type and the N-type layers of the cell. The connection to the P-type bottom layer isn't too difficult. A metallic plate at the bottom of the cell serves this purpose. The connection to the top N-type layer presents more of a problem.

The N-type layer is intentionally very thin so that light can penetrate through to the PN junction where the photovoltaic action takes place. Making a good connection to such a thin layer requires a precision process. The situation is further complicated by the fact that the metallic material used to make the connection will block some of the light that would otherwise penetrate to the junction. This blocking will reduce the efficiency of the cell.

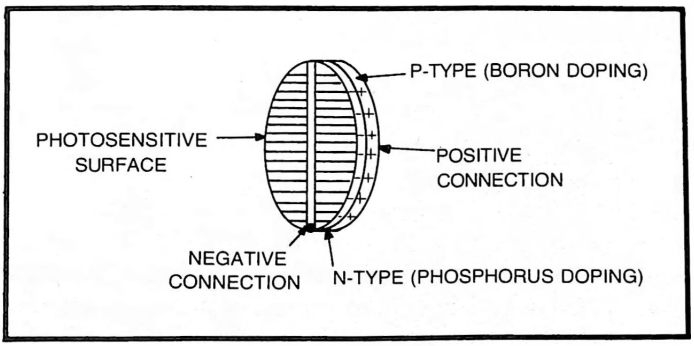


Fig. 4-2. Construction of solar cell.

The metallization used to make the connection must resist corrosion if the cell is to have a long life under outdoor conditions.

Another factor that can reduce the efficiency of a solar cell is reflection from its surface. Sunlight that is reflected from the surface will not penetrate to the junction, and will not be converted into electrical energy. Practical cells have a very thin antireflection coating similar to that used on photographic lenses. This layer reduces reflection without significantly blocking any of the incident light from the cell.

TEMPERATURE INFLUENCE

The silicon solar cell is normally rated for use between the temperatures of −65 degrees to +125 degrees Celsius (−85 degrees to +257 degrees Fahrenheit). The cell will withstand a temperature of up to +250 degrees Celsuis for a period of not more than 30 minutes, and even a temperature of 300 degrees Celsius for shorter periods of time.

Solar cells perform very well at extremely low temperatures. It is not uncommon to find a lower temperature limit as low as −100 degrees Celsius (−148 degrees Fahrenheit).

The temperature of a solar cell influences the amount of power that it will deliver for a given amount of illumination. As the temperature of the cell increases, the terminal voltage will decrease at a rate of about 2 millivolts per degree Celsius. This decrease in voltage is partially compensated by the fact that the current will increase at a rate of about 0.5 milliampere per degree Celsius. The compensation is not complete, however, and the net effect is that as the temperature of the cell increases the available power will decrease at a rate of about 0.3 percent per degree Celsius.

Figure 4-3 shows a plot of open-circuit voltage, short-circuit current, and maximum power output as functions of temperature. Inasmuch as the cell is rated for operation at a temperature of 25 degrees Celsius, the changes shown in the graph are zero at that temperature.

The curve of most interest is usually the maximum power output shown by the solid line. This curve shows that at temperatures below 25 degrees Celsius the power output actually increases. At higher temperatures, the power output falls off.

Instead of using the curves of Fig. 4-3 the effect of temperature can be found from the simple formulas in Fig. 4-4. Here a separate formula is used for temperatures above and below 25 degrees Celsius because the specification of the cell applies at this temperature.

SOLAR CELL SPECIFICATIONS

Individual solar cells, ideal for use as photosensors and for sun-powering small motors, electronic circuits, and thousands of other applications, produce up to 2 amperes of .45 volts. The microgenerators provide up to 40 ma at 1.5 volts and are particularly useful in applications requiring higher output voltage in a compact unit such as charging small batteries.

Typical features of solar cells include:

- High conversion efficiency, with chevron-pattern collector and tantalum oxide antireflective coating on most cells.
- Unique corrosion-resistant Trimet™ electrodes.
- Power output relatively constant over a broad temperature range.
- Operating range −65° C to 125° C.
- Easily wired in series or parallel for higher current or voltage.
- Current varies directly with light intensity, operating voltage available at a broad range of illumination levels (Fig. 4-5).

SERIES & PARALLEL CONNECTIONS

The power output of a typical solar cell is about the same as that from an ordinary flashlight battery. The voltage output

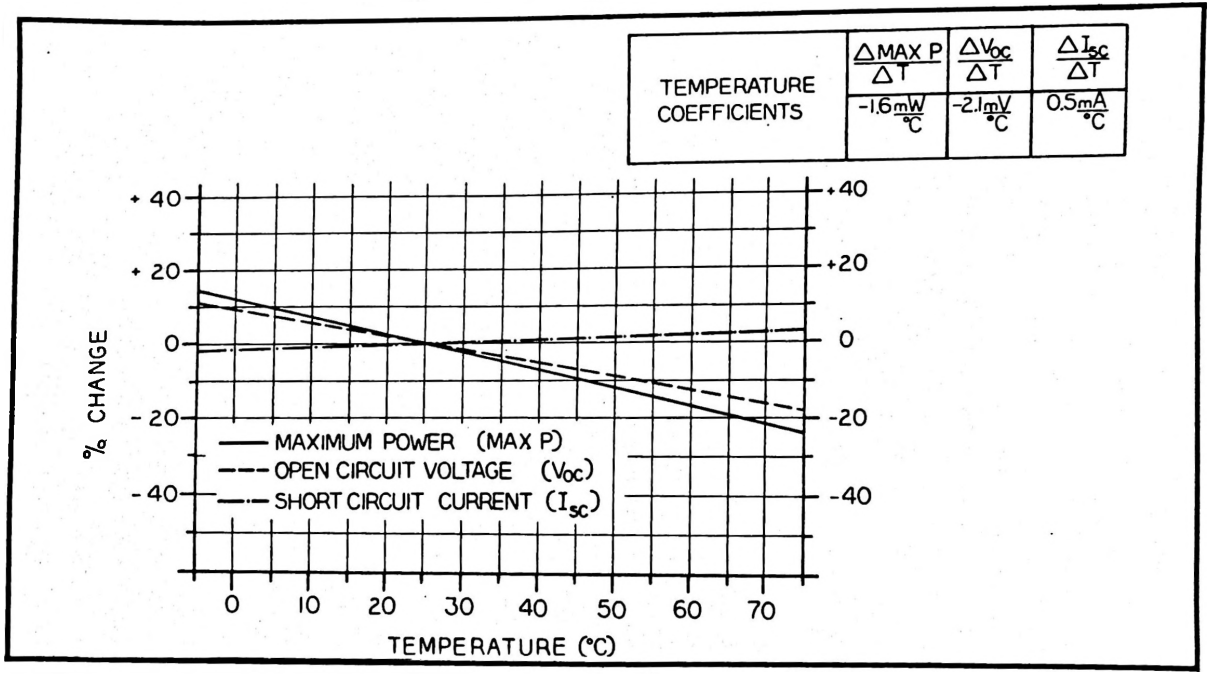


Fig. 4-3. Temperature characteristics of a typical solar cell.

$$E_{OUT} = E_{REF} [1 - 0.002 (T - 25)]$$

E_{OUT} = OUTPUT OF CELL IN VOLTS
E_{REF} = OUTPUT OF CELL IN VOLTS AT 25°C
T = TEMPERATURE IN DEGREES CELSIUS

$$I_{OUT} = I_{REF} [1 + 0.025A (T - 25)]$$

I_{OUT} = OUTPUT OF CELL IN MILLIAMPERES
I_{REF} = OUTPUT OF CELL IN MILLIAMPERES AT 25°C
A = AREA OF CELL IN SQUARE CENTIMETERS
T = TEMPERATURE IN DEGREES CELSIUS

Fig. 4-4. Equations for calculating solar cell output voltage and current at various temperatures.

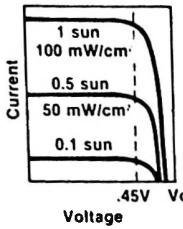
of a single cell is about 0.45 volts under full sun conditions. The amount of current produced by a single cell depends on its area. We can get an idea of the current output from the fact that the full sun output current of a 4-inch cell is about 2 amperes. Thus in many applications it is necessary to connect several cells together to form a generator that will supply the necessary voltage and current.

Solar cells can be connected in series and in parallel just like other cells such as flashlight cells. As shown in Fig. 4-6A, when several cells are connected in series, the total voltage from the assembly will be the sum of the voltages from the individual cells. The output current will be the same as that from a single cell.

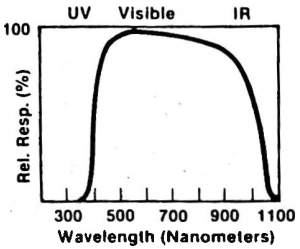
When cells are connected in parallel, as shown in Fig. 4-6B, the total current will be the sum of the currents from the individual cells, but the voltage will be the same as that from a single cell.

In most applications cells are connected in both series and parallel as shown in Fig. 4-7. Here the number of series

A. Typical Solarex Solar Cell I-V Characteristics



B. Typical Spectral Response (Quantum Yield) of Solarex Terrestrial Solar Cells



Solar Cells

E.S. Stock No.	Size	Output*	
		ma	V
602173003	4" dia.	2000	.42
602173006	10X10 cm	2000	.42
602173008**	1.6X.4"	40	1.5
602173002**	.65X.8"	12	1.5
602173004	2.5X5 cm	200	.42
602173005	5X5 cm	400	.42
602173020	5X10 cm	1000	.42

*Standard test conditions: 25°C, 100mW/cm² (1 sun) insolation
** Microgenerators

Fig. 4-5. Typical solar cell characteristics and specifications.

groups of cells will determine the voltage and the number of parallel cells in each group will determine the current that can be delivered to a load.

SOLAR PANELS

When several solar cells are connected together in series parallel to obtain the desired voltage and current ratings the assembly is called a solar panel, Unipanel®, or a solar Energizer®. Figure 4-8 shows a Solarex SX® Series panel. This particular panel will deliver up to 40 watts of electrical power at 12 volts.

The actual construction of a solar panel depends to a large extent on the conditions to which it will be subjected in any particular application. In the Unipanel type of construction the

cells are mounted on a rigid random-fiber polyester board. The cells themselves are usually encapsulated in a highly transparent silicone rubber. Although this encapsulation provides a great deal of protection to the surface of the cells, some severe environmental conditions require additional protective coverings in addition to the silicone rubber. Coatings of glass, Plexiglas, or Lexan are available when required for extra protection against possible cell damage from hailstones, dust, salt air, and similar environmental influences.

Another important consideration in the design of a solar panel is the leads that make the electrical connections to the cells. Normally, the metal used to make these electrical con-

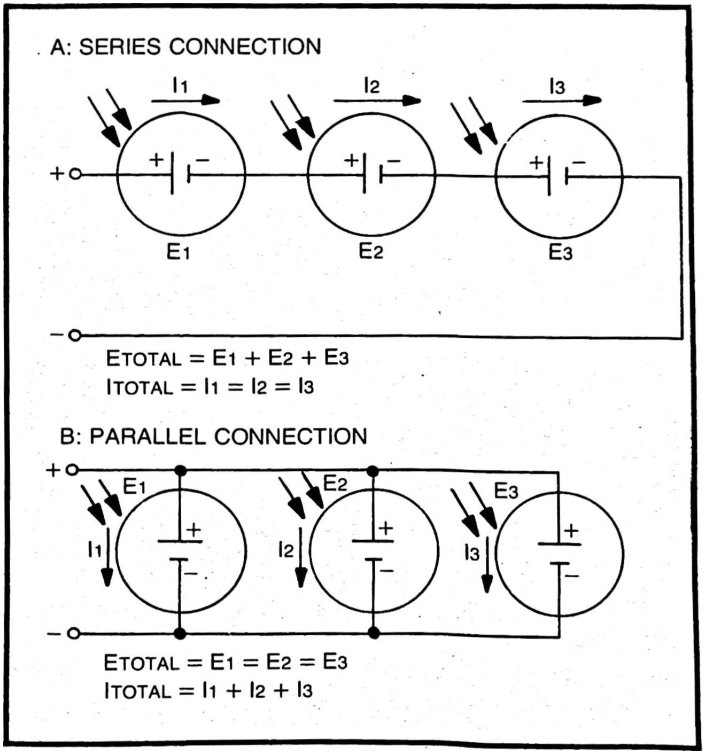


Fig. 4-6. Solar cells connected in (A) series and (B) parallel.

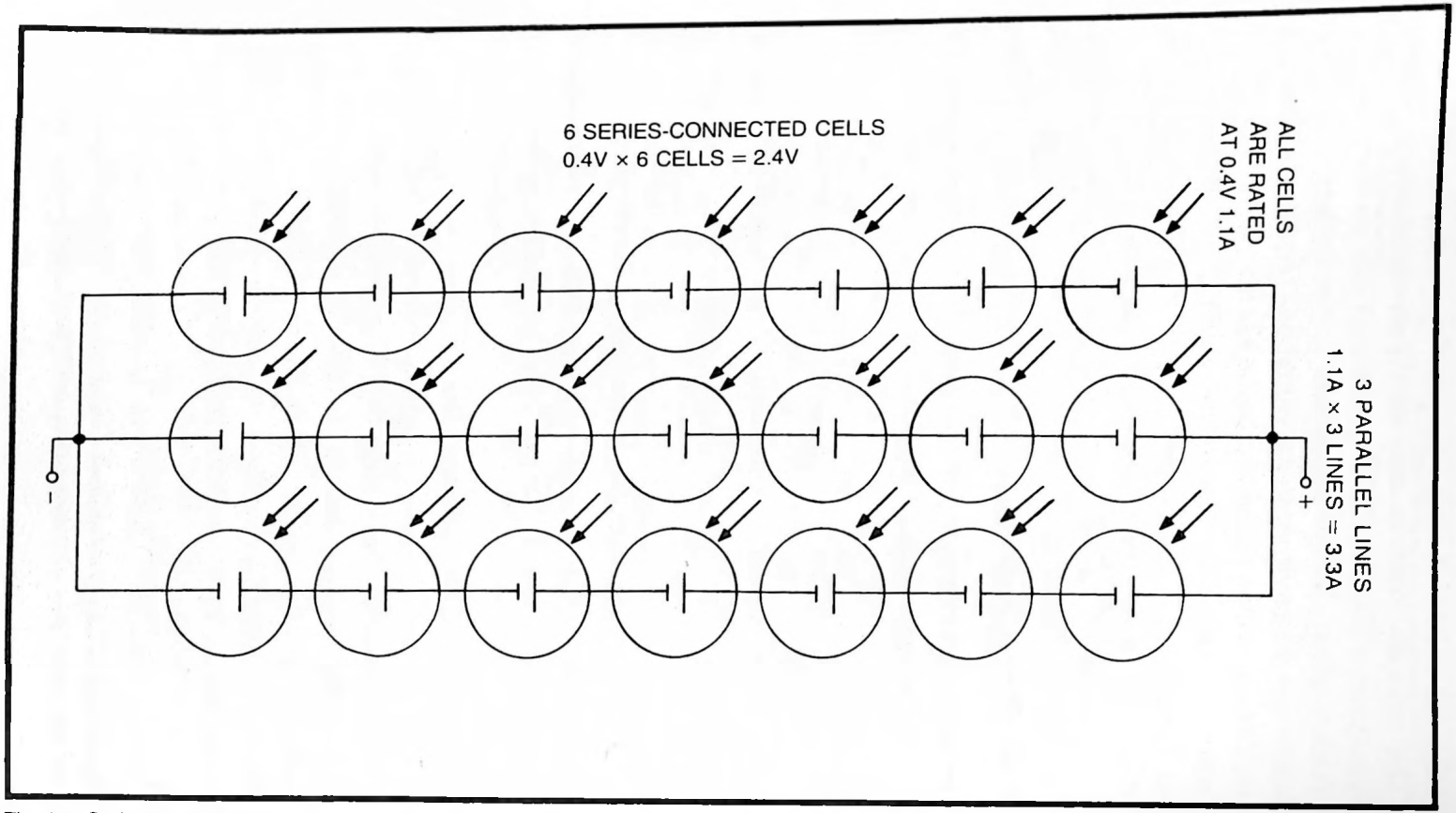


Fig. 4-7. Series-parallel connection of solar cells to provide any voltage and current rating. These cells are rated at 0.4 volts at 1.1 amperes each.

nections would be subject to corrosion. In a well designed panel, such as the one shown in Fig. 4-8, the metallization used to make the electric connections in the panel is completely protected from the environment. This type of panel construction provides a very durable, weather-resistant package that requires practically no maintenance.

Looking at Fig. 4-8, you will notice the new Solarex SX Series panel uses square solar cells. Using such cells, virtu-

Fig. 4-8. The SX Series solar electric panel from Solarex is the state of the art in solar electricity. These panels produce between 32 and 40 watts of power under full sun.

ally the entire surface area of the panel can be devoted to generating electricity. Circular or semicircular cells can also be arranged efficiently on a panel substrate, but there will almost always remain some area between cells that is not photovoltaically active.

The Solarex 4330EG panel illustrated in Fig. 4-9 uses circular cells and produces peak power of 33.5 watts at 14 volts under full sun.

CONCENTRATOR CELLS

In all of the applications of solar cells that we have discussed thus far, the output of a solar cell or panel is limited by the amount of sunlight that will be intercepted by its area. The question naturally arises as to why we can't use some sort of focusing arrangement that will capture sunlight from a larger area and focus it on the solar cell. The principle is shown in Fig. 4-11. Here a focusing lens, very much like an ordinary magnifiying glass, is used to focus sunlight from an area six inches in diameter onto the surface of a solar cell having a diameter of only three inches. If the power density from the sunlight is 100 mW/cm^2, then the density at the solar cell should be 200 mW/cm^2. Obviously such an arrangement would have advantages in some applications.

The reason that such arrangements haven't been used until rather recently is that ordinary solar cells have been unable to handle the high power density that would result from focusing. A comparatively new type of solar cell, called a concentrator cell, will allow the use of focusing arrangements where the power density at the surface of the cell may be up to two hundred times the normal power density of sunlight.

A typical concentrator cell may have an area of 4 cm^2 to 25 cm^2 or even larger. The thickness usually ranges from 2 mils (50.8 microns) to 14 mils (355.6 microns). The construction of the cell is such that it will withstand very high light concentration without damage and will still provide a linear power output. Figure 4-12 shows the pattern of electric connections to

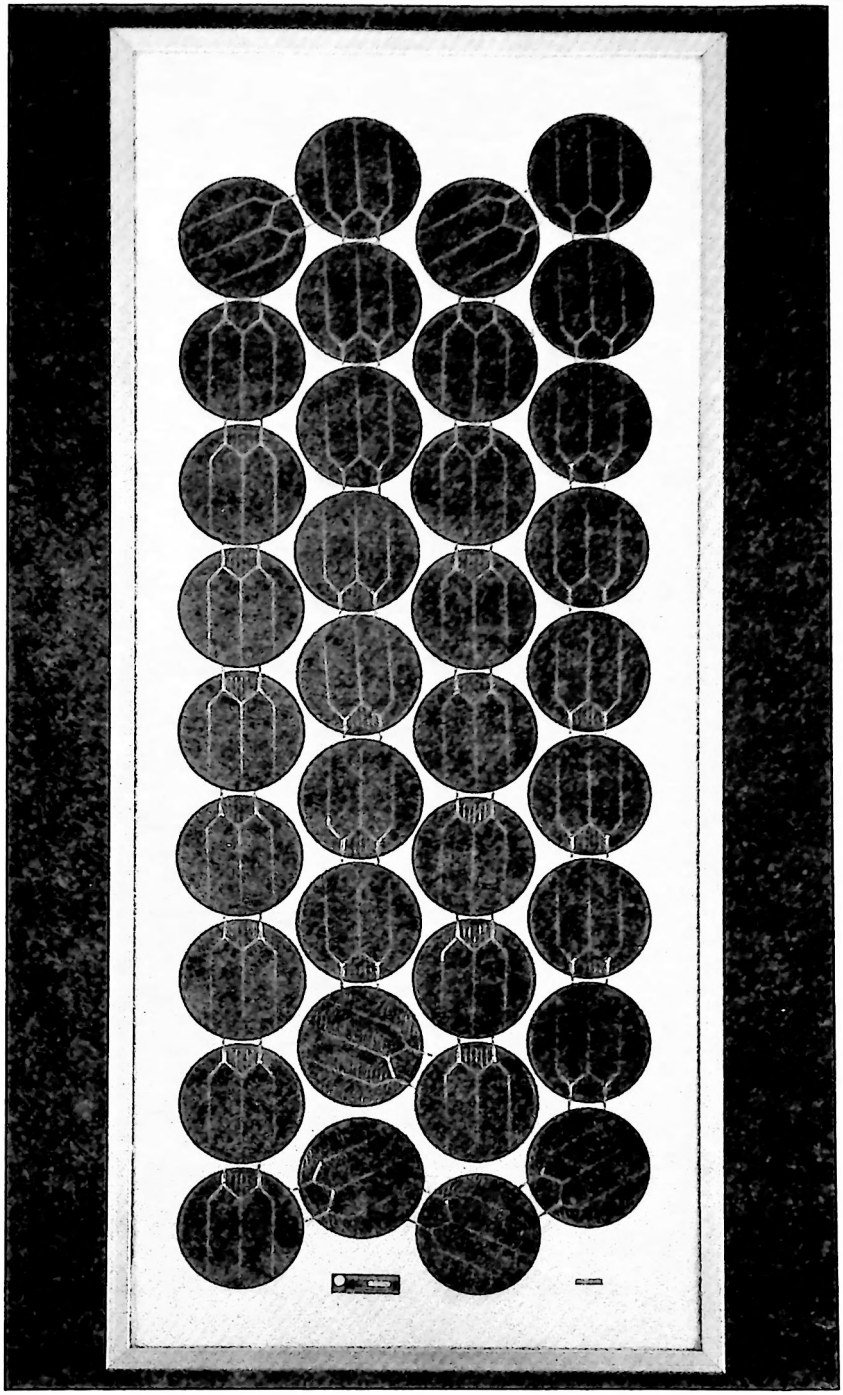


Fig. 4-9. The Solarex 4330EG solar panel uses 36 circular solar cells to produce peak power of 33.5 watts at 14 volts under full sun. This panel measures 44 by 17 inches.

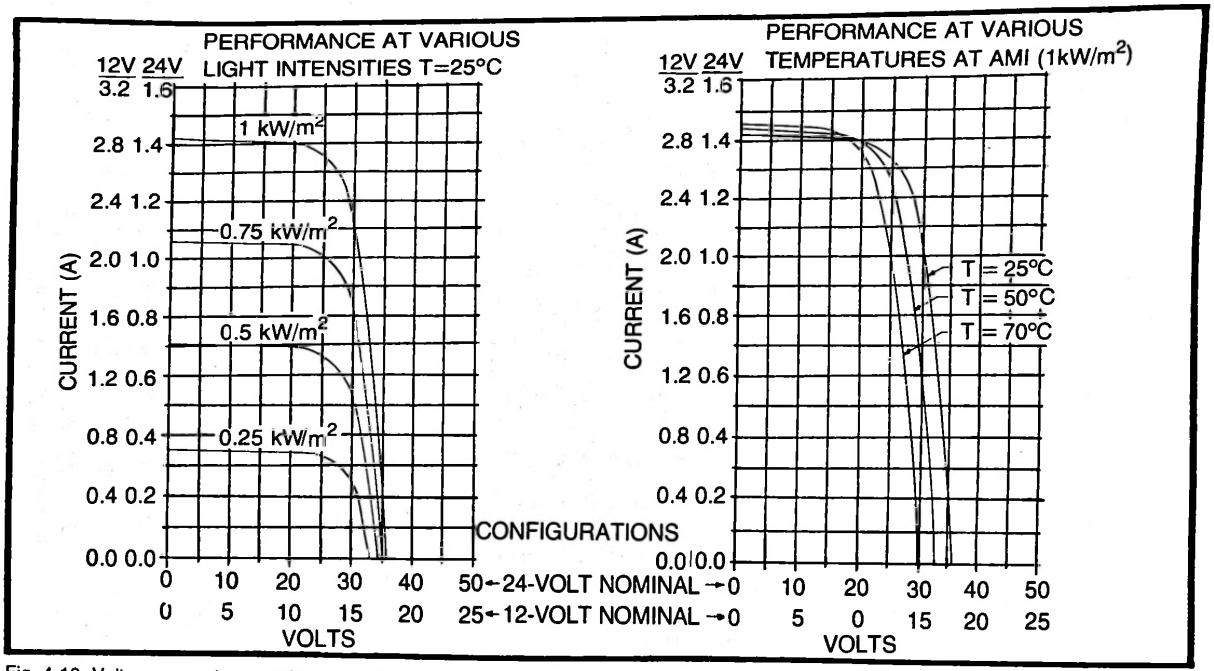


Fig. 4-10. Voltage current curves for a typical solar panel.

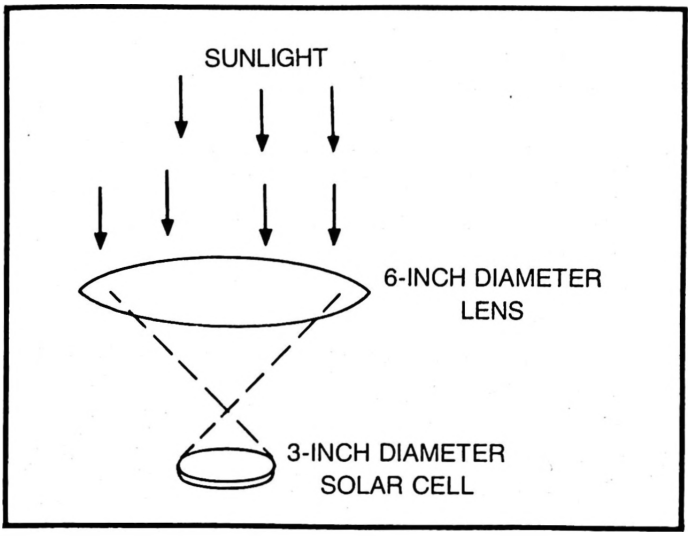


Fig. 4-11. Principal of focusing to concentrate light on a solar cell.

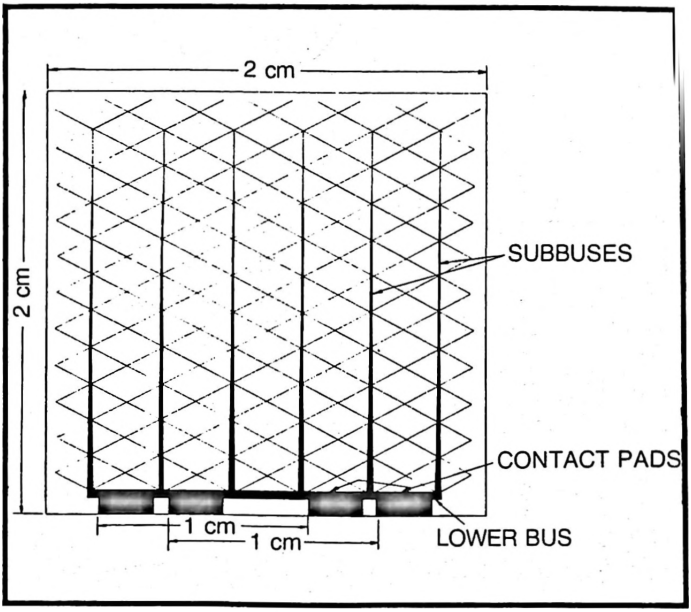


Fig. 4-12. Electric connection pattern of a high-efficiency concentrator cell.

such a cell. Note that the metallization used to make the connections is such that it will block very little of the incident sunlight, thus improving the efficiency of the cell.

Concentrator cells are often assembled into large panels to provide large amounts of power. Because of the concentration of the sunlight, the temperature at the cell will be higher than that of a conventional solar cell. This feature can be used to advantage by using water, or some other coolant, to cool the panel. When this is done, the system will provide thermal energy in some form such as hot water in addition to the electrical energy. The overall energy conversion efficiency of a concentrator panel can be made very high because of the additional thermal energy.

Figure 4-13 shows the voltage-current curves for a typical concentrator cell under full sun conditions. The various curves are for different cell temperatures. Note that the power output of a concentrator cell is lower at higher cell temperatures, just as in an ordinary solar cell. This shows that

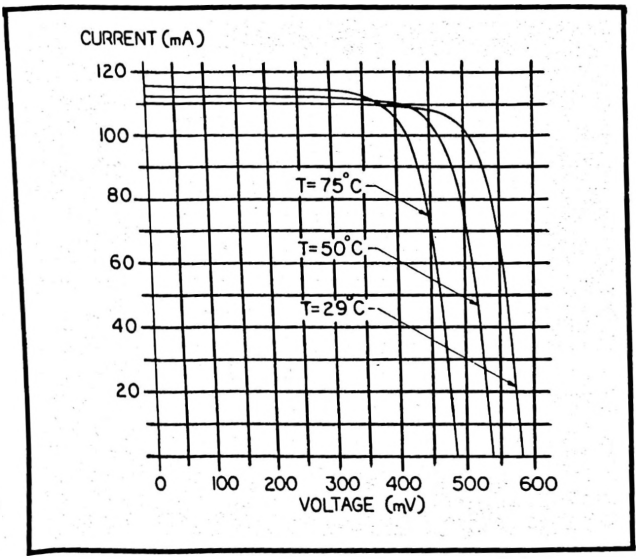


Fig. 4-13. Voltage-current curves for a typical concentrator cell.

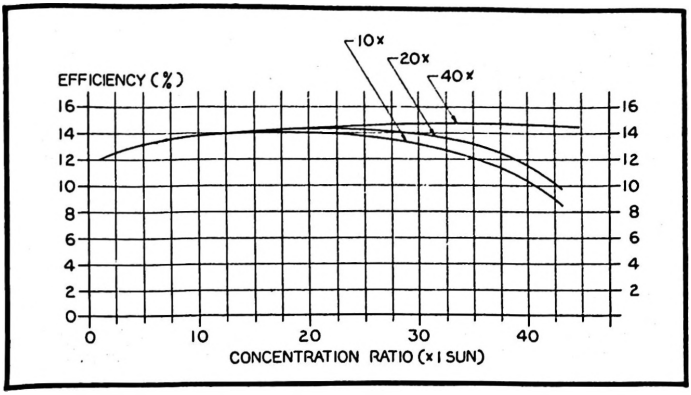


Fig. 4-14. Efficiency of a concentrator cell at various concentration ratios.

if we use a coolant to collect thermal energy in addition to the electrical energy and thus lower the temperature of the cell, we will actually increase the efficiency of the cell.

The efficiency of a concentrator cell also increases with light concentration. This is shown in the graph of Fig. 4-14. Here the concentration ratio is simply the amount of magnification of the incident sunlight. For example, if the concentration is forty times, the power density at surface of the cells will be forty times the power density of the incident sunlight.

Figure 4-15 shows a low concentration array that will provide over 100 watts of peak power. Each of the six panels in the array contains seventeen high-efficiency concentration cells with integral mirrored reflectors that provide a geometric concentration ratio of two times. The electrical performance of the array is tabulated below.

Peak power .....112 watts
Voltage at peak power .....48 volts
Current at peak power .....2.3 amperes
Open circuit voltage .....57 volts
Short circuit current .....2.5 amperes

Measurements on the array shown in Fig. 4-15 show that during the daylight hours of a typical day the effective concentration ratio averages over 1.6 times. The energy produced is

about 480 watt-hours per day. By way of comparison, a typical flat panel with the same active photovoltaic area would produce only about 284 watt-hours under the same conditions.

SOLAR MICROGENERATORS

We noted earlier that solar cells come in a wide variety of sizes. In addition to the larger units that are used to supply large amounts of power, there is a need for very small photovoltaic devices to supply operating power for devices such as electronic watches, calculators, and flashlights.

Figure 4-16 shows an assortment of Microgenerators which are used for this purpose. Most frequently, Microgenerators are used to recharge very small batteries that supply power to devices that use very little power, but there are some devices where all of the operating power comes directly from a Microgenerator.

The assemblies are designed to be very efficient at both high and low light levels. The low light level efficiency is very important in such applications as electronic watches or calculators because these devices are usually used under conditions of low illumination such as shade or room light.

Because of their attractive appearance, Microgenerators are often used as a part of the decorative design of devices such as a watch or a calculator. The silicon surface may have either a shiny or a mat appearance which can be blended in with the overall appearance of the device in which it is used. Microgenerators can also be supplied in colors.

The Microgenerator is actually made up of several extremely small solar cells connected in series. Figure 4-17 shows how the cells are put together into an array. Figure 4-18 shows the voltage-current curves of both a standard Microgenerator and one that includes voltage regulation. These curves will be confusing at first, because the coordinates are different than those that we have been using for solar cells. In this illustration we have plotted voltage along the

Fig. 4-15. Low concentration array.

Fig. 4-16. Assorted Microgenerators used to power calculators and watches.

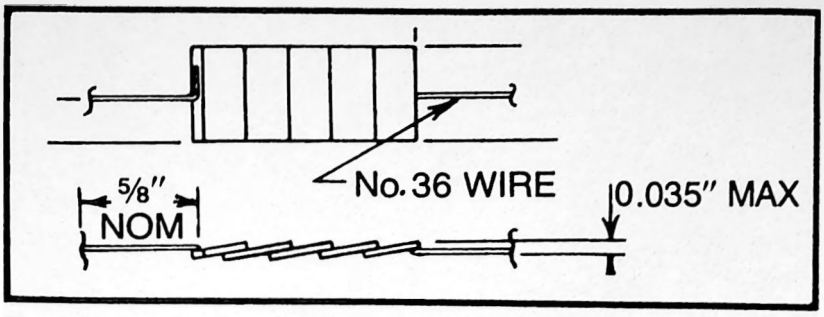


Fig. 4-17. Construction of a Microgenerator array.

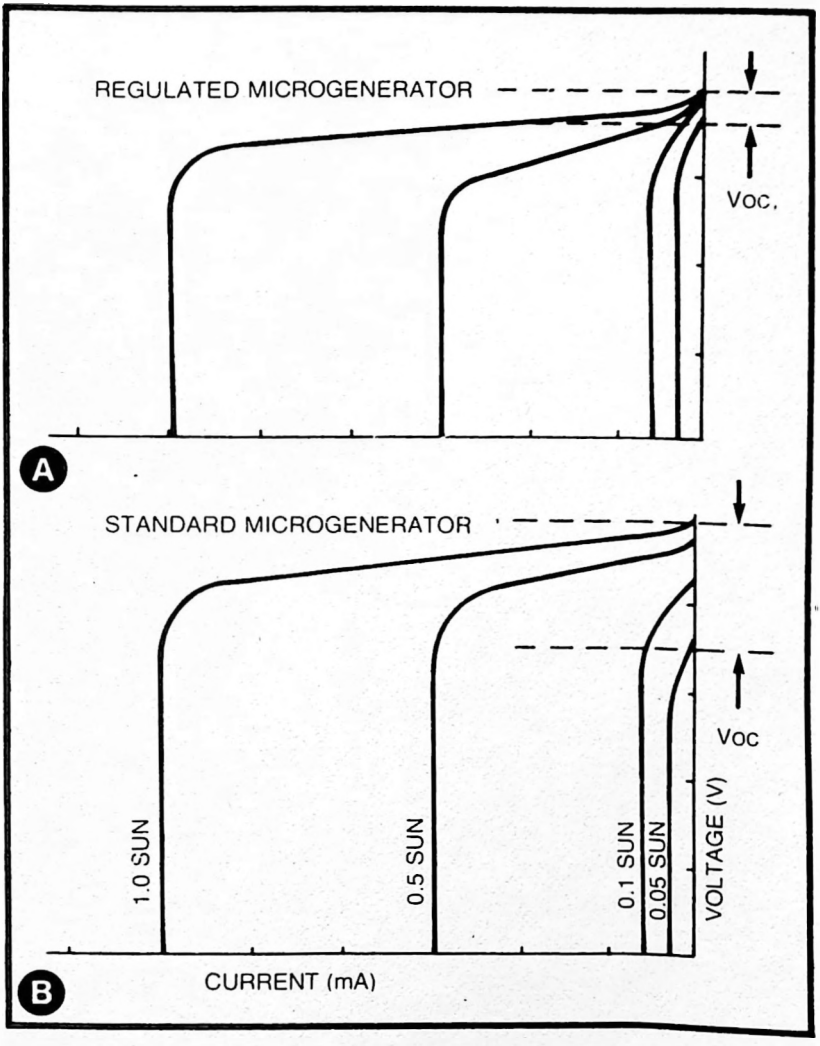


Fig. 4-18. Voltage-current curves of (A) a regulated, and (B) a standard Microgenerator array.

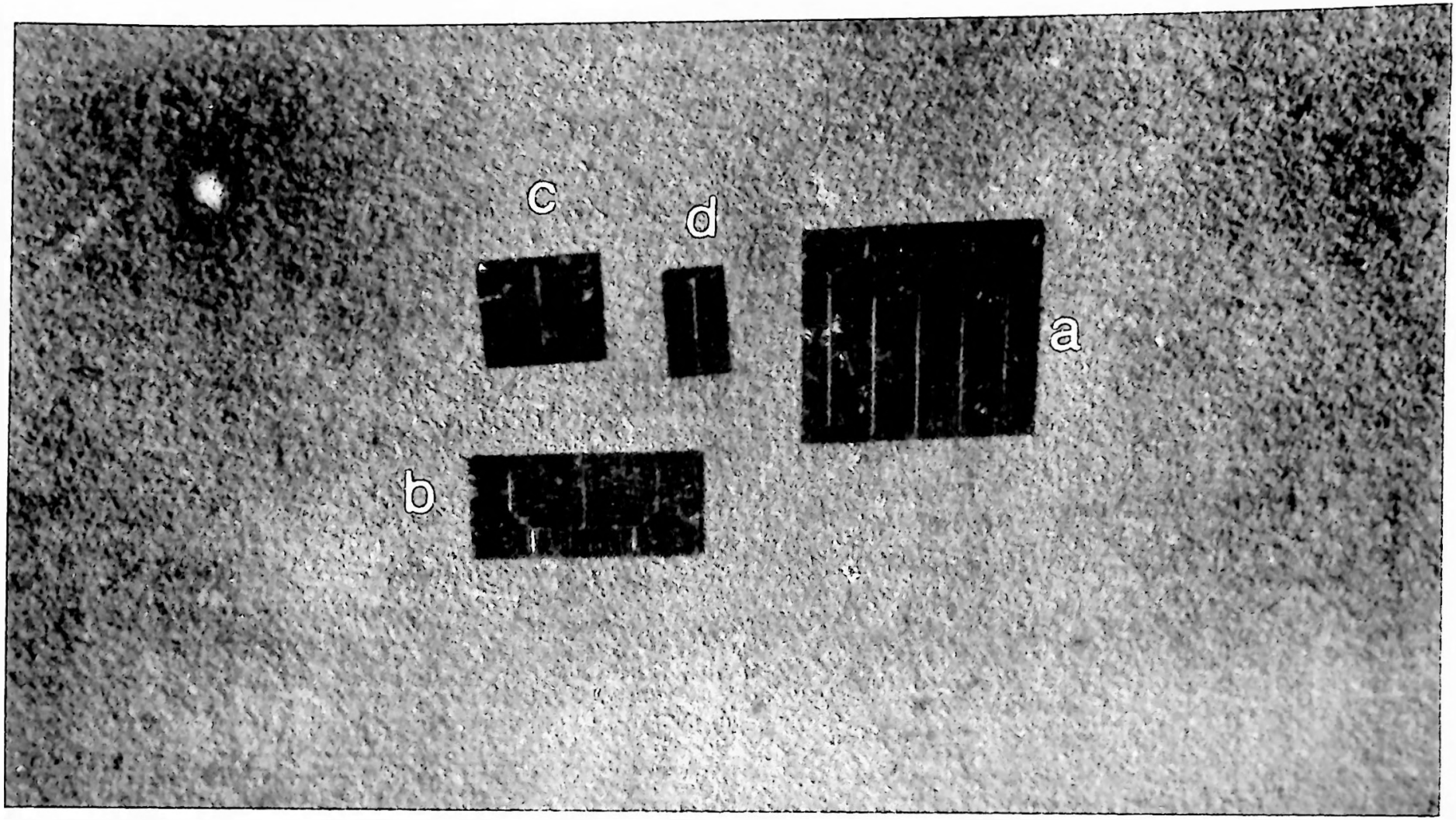
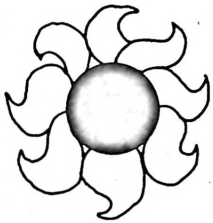


Fig. 4-19. Solarex solar cells in (a) 10 cm × 10 cm, (b) 5 cm × 10 cm, (c) 5 cm × 5 cm, and (d) 2.5 cm × 5 cm sizes.

vertical axis and current along the horizontal axis. Note that with the regulated arrangement the open circuit voltage changes very little with varying light conditions.

Chapter 5

How to Use Solar Cells



Solar cells are very easy to use as compared to most other energy sources. A solar electric system has no moving parts and usually requires little if any maintenance. Some analysis is required in the design of a system, but the process is very simple. A good design can be obtained using only graphs and simple arithmetic. Computer programs are available that will optimize the design of any system, regardless of size.

There are two principal considerations in the design of any solar electric power system. First we have to know how much sunlight is available at the proposed site and how it varies with the seasons of the year. This will tell us the size of the solar electric generator needed to supply any given amount of power. Next, we must know the characteristics of the load including the average current requirement and the duty cycle. This tells us how much storage battery capacity we will need to keep the system operating when sunlight isn't available.

AVAILABLE SUNLIGHT

Finding the amount of sunlight that reaches the earth in any given location usually doesn't require any measurements.

Government agencies interested in agriculture and weather forecasting have been recording the amount of sunlight in all parts of the country for many years. Usually these records can be used to determine the number of solar cells required for any particular application.

Some caution must be used in applying these figures because they may not apply directly to a solar electric installation. The first problem is that sunlight is usually recorded in terms of a unit called the langley. One langley is equal to 11.62 watt-hours per square meter. It is easy enough to convert from langleys to watt-hours, but there is another consideration. The published figures usually represent the sunlight reaching a square meter of the earth's surface, that is, the energy incident on a horizontal plane. Solar cells are usually tilted so that they intercept the maximum amount of energy all through the year. Therefore the inclined solar cell array will usually intercept more energy than an equivalent horizontal surface flat on the earth.

A much more useful measure of solar radiation is one which expresses the average number of *peak sun hours per day* for a particular location. Figure 5-1 shows such a map. The radiation figures have been corrected to account for the solar cell panel being tilted at an angle of 45 degrees and oriented due South. This has been found to be the optimum orientation for panels in most parts of the United States.

The numbers in Fig. 5-1 are a yearly average. These will be somewhat lower during periods when sunlight is diminished. Figure 5-2 shows a map where the figures are the peak sun hours per day averaged over a *four-week period* from December 7th through January 4th. Note that these figures are somewhat less than those of Fig. 5-1. Figure 5-3 shows the worldwide distribution of peak sun hours per week.

In all cases, it has been assumed that the solar cells would not be in the shade during part of the day. This is the preferred way to install a system. There will be some places, however, where it isn't practical to find a spot to mount the solar array where it won't experience some shade, at least

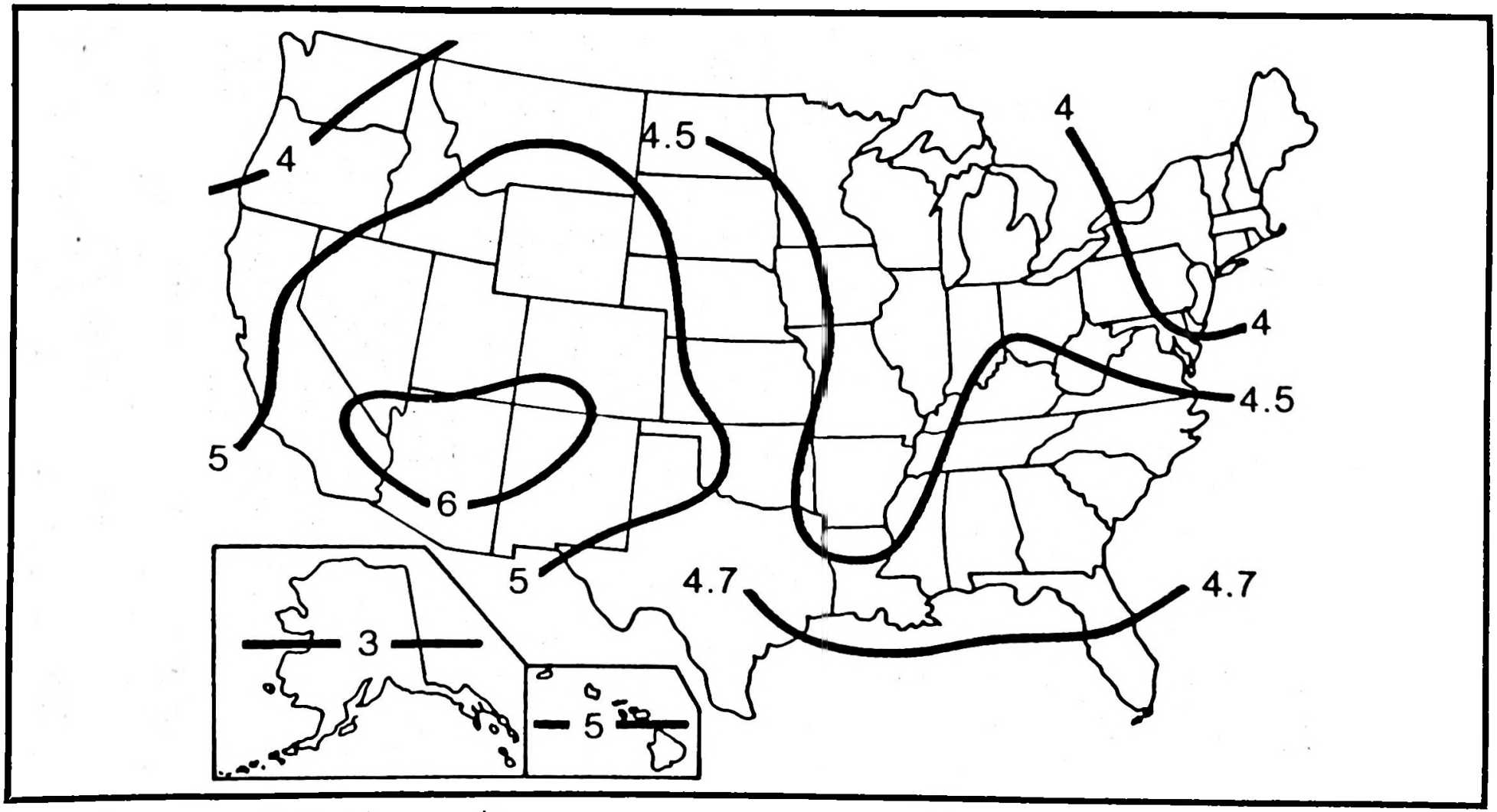


Fig. 5-1. Yearly average peak sun hours per day.

part of the time. In such applications allowance must be made for the shade. This usually means that more solar cells will be required to furnish a given amount of power.

LOAD REQUIREMENTS

Normally the power rating of an electric device is given in watts. This, of course, is the rate at which the device consumes electrical energy. The total daily energy requirement of a device is specified in watt-hours or kilowatt-hours.

In an earlier chapter we saw that the voltage from a solar electric generator is nearly constant. Most systems include storage batteries which also tend to have a constant voltage output. For this reason, we can quite conveniently specify the power consumption of an electric device in terms of amperes. In this case the daily energy requirement will be in ampere-hours.

By stating the energy requirement in ampere-hours we can easily match a load to a solar generator and determine the size of the solar generator required for that particular load.

If the load is something that draws a constant current, the problem is rather simple. Suppose, for example, that we wish to use solar energy to operate an electric clock that draws a current of 20 milliamperes. The load current in amperes is simply 0.02 amperes and the daily (24-hour) energy requirement in ampere-hours is

$$\text{Ampere-hours} = 0.02 \times 24 = 0.48$$

INTERMITTENT LOADS

Most of the loads that we might wish to operate from a solar electric generator will not draw a constant current. For example, a two-way radio station draws much more current when it is transmitting than when it is receiving. Similarly, a water pump usually pumps on demand, drawing maximum current while it is pumping and practically no current while it is idling. Of course, the varying voltage and current requirements of different applications are no problem because solar

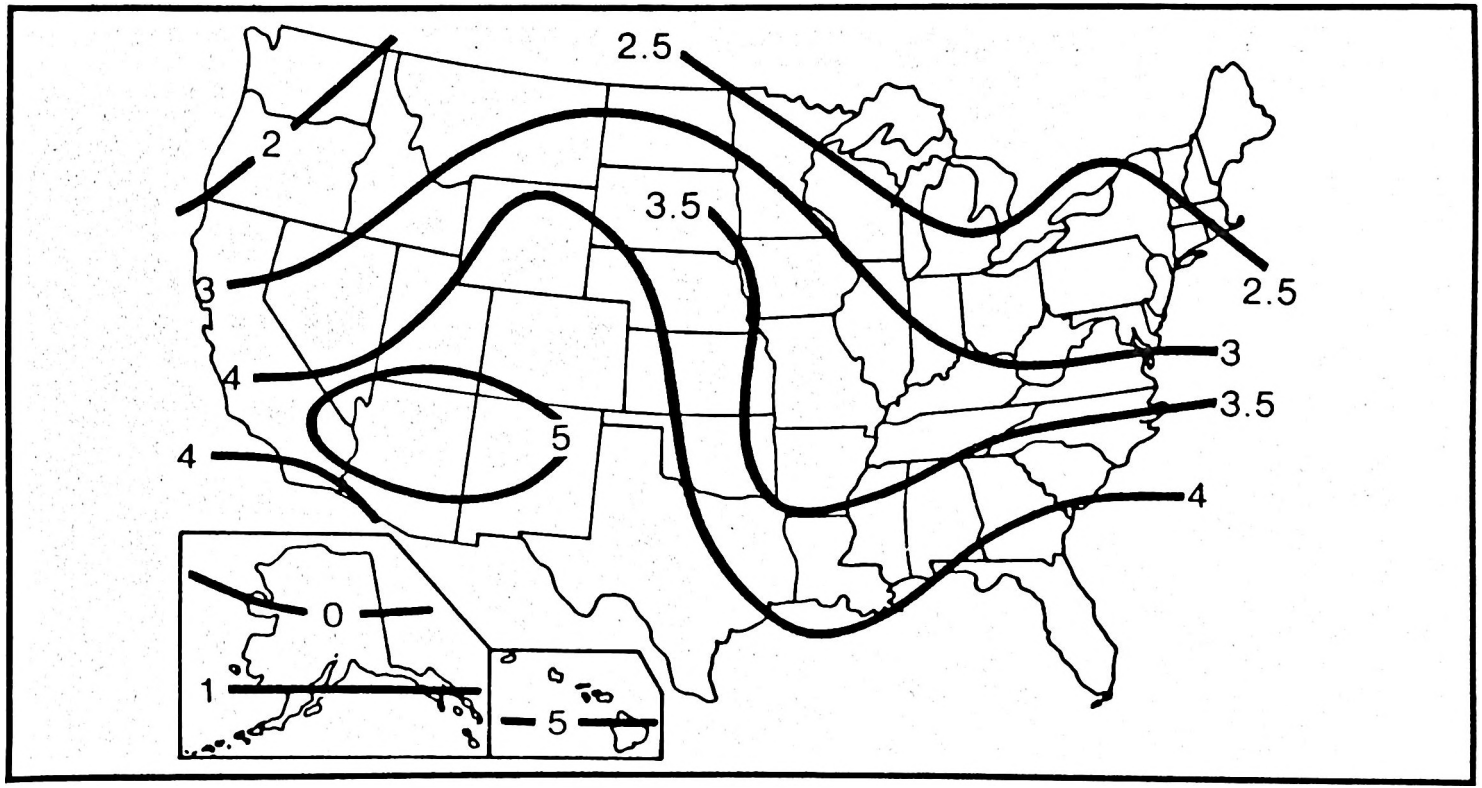


Fig. 5-2. Peak sun hours per day for a four-week period from December 7th to January 4th.

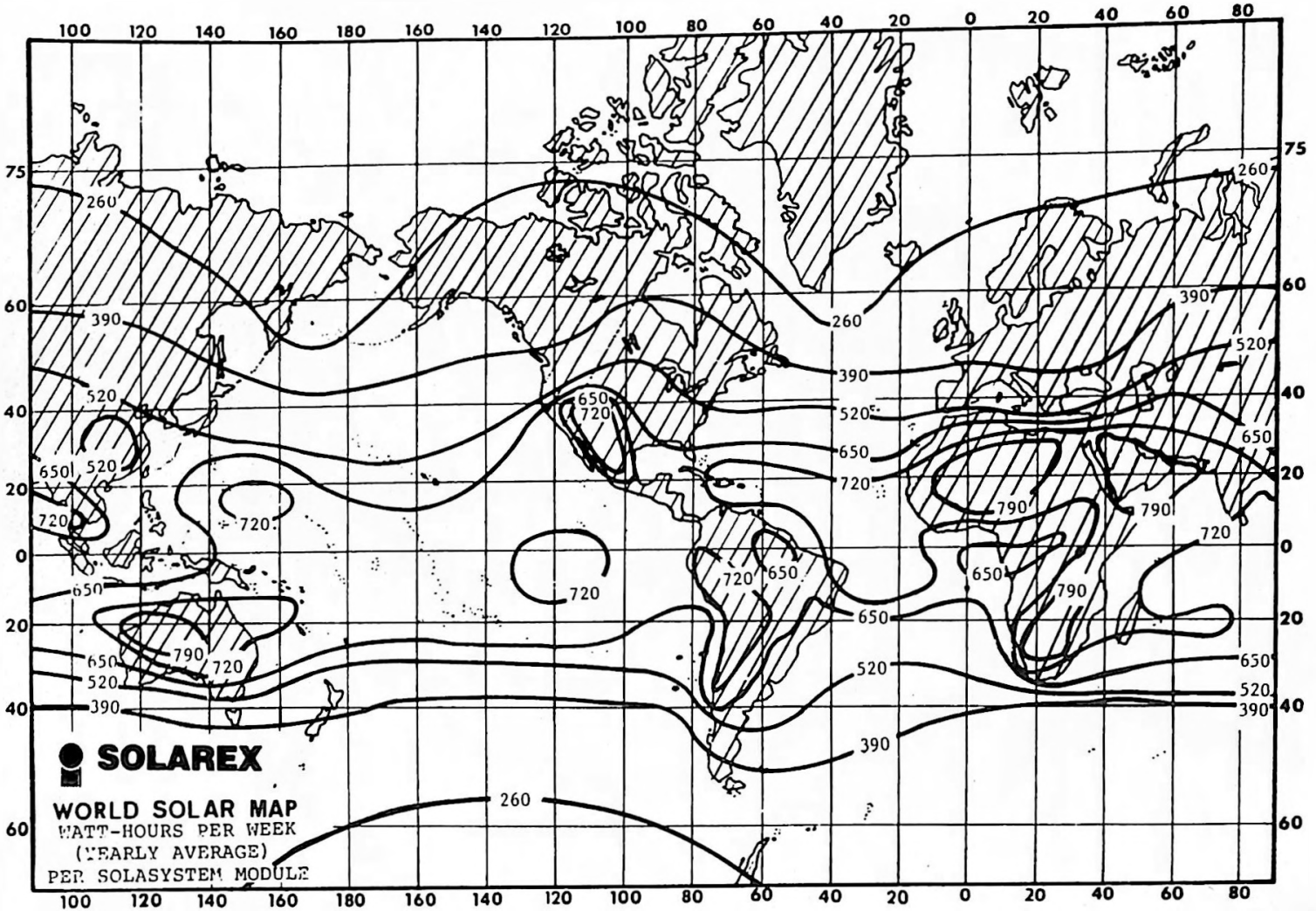


Fig. 5-3. Worldwide distribution by sun (watt-hours) per week (yearly average) per solasystem module.

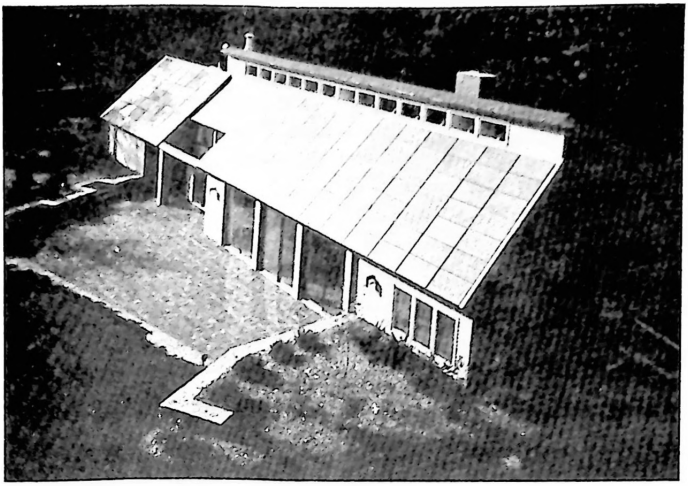


Fig. 5-4. This house in Carlisle, Massachusetts, uses a rooftop solar array to generate up to 7.3 kW of electric power for all household uses.

cells can be connected in any series-parallel configuration required to provide the necessary voltage and current.

The easiest way to determine the average current, as well as the total daily load in ampere-hours, is to make a tabulation of the amount of current drawn at various times over a 24-hour period. Once this information is available, the design of the system is quite simple as shown in the following example.

We have a two-way radio repeater which is located on a remote mountain top where its antenna will provide good coverage. The area is not near any power lines so we wish to power the repeater with a solar electric generator. When the repeater is transmitting, it draws 5 amperes of current. While it is idling, it only draws about 1 ampere. A study of the system shows that it only transmits about ten percent of the time during any 24-hour period. Knowing these facts we can find the number of ampere-hours required for a 24-hour period.

$$\text{Transmitting } 5 \times 0.10 \times 24 = 12$$
$$\text{Idling } 1 \times 0.90 \times 24 = 21.6$$
$$\text{Total } 12 + 21.6 = 33.6$$

Thus, with very little effort we have found that the average daily load of the repeater is 33.6 ampere-hours. To find the average current, we merely divide this figure by twenty-four hours.

$$\text{Average amperes} = \frac{33.6}{24} = 1.4$$

A tabulation of this type can be prepared for any type of load. Once we have the load requirement, we can determine the size of solar generator required to do this job.

SYSTEM CALCULATIONS

Knowing the average number of peak sun hours at a proposed site and the average daily load requirements in ampere-hours, we can quite readily calculate the total current output necessary from the solar generator. The following equation shows how this is done:

$$\frac{\text{Average daily load}}{\text{Peak sun hours}} \times 1.2 = \text{Amperes required}$$

The factor of 1.2 is included to take care of inevitable system losses. The number of solar panels needed to provide this current can be found by dividing the total current by the current output of an individual panel. That is,

$$\text{Total panels} = \frac{\text{Amperes required}}{\text{One-panel current}}$$

To illustrate the use of these equations, consider a two-way radio repeater system installed in Kansas City, Missouri. The repeater operates continuously, twenty-four hours a day, and draws an average current of 2 amperes. Reference to Fig. 5-1 shows a daily average of 4.5 peak sun hours at the site. Using the first of the above equations, we find

$$\text{Amperes required} = \frac{2 \times 24}{4.5} \times 1.2 = 12.8$$

The nominal operating voltage of the repeater is 12.8 volts so the solar panels will be used to maintain a charge in a 12-volt battery. It has been found through experience that a solar generator with a nominal terminal voltage of 14 volts is well suited to such an application. Thus the Solarex Type SX20 panel which has an output current of 1.05 amperes at a nominal terminal voltage of 12 volts, was selected as the basic element of the solar array. Using the second equation given above, we find that

$$\text{Total panels} = \frac{12.8}{1.5} = 12.19$$

In practice the number 12.12 is rounded off to 12, and the generator for the system consists of twelve SX20 panels connected in parallel.

Note that we selected a panel that produced the required voltage and used our equations to find the number of panels required for the application.

If the repeater drew the same current as the one in our example, but operated at 24 volts, we use 12 more panels in series with those in the example. This would give us a nominal terminal voltage of 24 volts, which has been found to be suitable for use with 24-volt batteries.

This type of system calculation will lead to a conservative design that will be highly satisfactory in most applications. It is possible to make a much more detailed analysis by using the equations to predict the performance for every month of the year. In some instances this may result in a more economical design. A computer program for the purpose is available from Solarex.

BATTERIES

In the preceding discussion of load requirements we considered the load requirement over a 24-hour period without regard to the fact that sunlight will not be available during the full 24-hour day. Any solar generator which might be called

on to furnish energy at a time when light is not available must include a storage battery.

The function of a battery in a solar electric generator is twofold. The battery must furnish power to the load when sunlight is not available, and it also must smooth out variations in the load. All the solar panel has to do is to furnish the average daily load requirement. Naturally, all of this energy will be generated during daylight hours. The battery will store the energy and make it available to the load as required.

Many different types of batteries are available, each having its advantages and limitations. Batteries are usually classified into two general types—primary batteries and secondary batteries. The primary battery is one that cannot be recharged and is of no interest in solar electric generators. The secondary battery is a storage battery that can be recharged many times and is the type in which we are interested. Strictly speaking, the word battery should apply to a collection of separate cells, but common usage applies the term to any device that furnishes electrical energy, even though it might be a single cell. The ordinary flashlight battery is a good example. It is almost always called a battery, although it is really a single cell.

There are many different types of storage batteries commercially available. Selection of a battery type for a particular solar electric generator involves many considerations. Included among these are:

- Voltage requirement
- Current requirement
- Operating schedule
- Ampere-hour capacity
- Operating temperature range
- Size and weight
- Required life
- Cost

TYPES OF BATTERIES

By far the most common type of battery used in solar

electric generators is the lead-acid battery. The familiar automobile battery is a good example of this type. Until comparatively recently, the lead-acid battery was a vented unit with removable caps used to refill the electrolyte. This type of battery is probably still the most economical type. It can deliver relatively large currents at a nearly constant voltage for long periods of time. It has the limitations that it requires periodic maintenance, operates poorly at very low temperatures, and vents hydrogen gas during the charging period. In some applications, the hydrogen gas may constitute an explosion hazard.

Several different types of sealed lead acid batteries have become available in recent years. These are usually more expensive than the vented battery, but the saving in maintenance can often justify the additional cost. Sealed automobile batteries carrying a five-year maintenance-free warranty are readily available. These batteries are well suited for use in many solar electric generators.

One type of sealed lead-acid battery uses a gelled electrolyte. Although this battery is sealed, the seal is a resealing type that will vent gasses if the internal pressure should become too great. Thus there is no danger of explosion if something should go wrong in the system. During the normal charge and discharge cycles, the pressure never becomes great enough to operate the vent.

There are two separate types of batteries using gelled electrolytes. One type is designed for the battery to be floated across a line at all times so that it will furnish power only when the regular power source fails. The other type is designed for regular charge and discharge cycles.

There is another type of sealed lead-acid battery called a "starved electrolyte" type. Again this type of a battery is vented with a resealable vent, but usually the pressure is much higher than in the type described above. As a result, this type will withstand higher current discharges without loss of electrolyte.

Still another type of sealed lead-acid battery is truly

sealed. The chemistry of the battery is such that under conditions that would normally increase the internal pressure in the cell, the process is stopped before the internal pressure can become excessive.

For smaller loads, the most common type of storage battery used is the sealed nickel-cadmium battery. This is the familiar rechargeable battery that is used in calculators and portable walkie-talkie radios. One of the disadvantages of the nickel cadmium, or nicad as it is often called, is that it tends to develop a memory. If it is continually operated with the same charge-discharge pattern, it will want to follow this same pattern. For example, if a nicad is operated in an application where it is allowed to discharge about twenty-five percent before recharging, it will tend to loose its capacity to be discharged lower than about twenty-five percent.

Two other types of storage battery—silver cadmium and silver zinc—have a very high energy density; that is, they will produce more kilowatt-hours of energy per pound of battery than other types. They are more expensive but well suited to applications where a very small battery is required and it is desirable to get as much energy as possible stored in the small volume. Typical applications for these batteries include portable electronic equipment and military devices. The silver-zinc battery, sometimes called a silver-oxide battery is used frequently in electronic watches.

BATTERY SPECIFICATIONS

Earlier we listed some of the factors that must be considered in selecting a battery for any given solar electric generator. In practice, the best policy is to contact the battery manufacturer for a recommended type for any application. The following information will give a general idea of how the various requirements of an application affect the choice of a type of battery.

Voltage Requirement

It goes without saying that a battery must not supply

voltages high enough to damage the equipment that is being powered. This is usually prevented by the use of voltage regulating circuits in the equipment. Another voltage consideration centers around the fact that many electronic items will not operate at all when the supply voltage falls below a certain value. Figure 5-5 shows how the voltage of nickel-cadmium batteries falls off as the battery becomes discharged. Note that the terminal voltage of the nicad holds comparatively constant through much of the discharge cycle. This shows that the nicad might be the better choice in applications where the low end voltage of the cycle is critical.

Current Requirement

In some applications the current drain will be nearly constant. In others the system will be required to supply a large current for a short period of time. Usually the sealed nicad is best suited for supplying short bursts of high current, but the lead-acid battery will also handle such requirements.

Operating Temperature

Most storage batteries will work well at reasonably low temperatures. The lead-acid battery will operate at lower temperatures than the nicad. In either case, the output of the battery tends to be lower at lower temperatures. For this reason, any application where the batteries will be exposed to low temperatures, as at high latitudes, will require additional battery capacity because of this factor.

Size & Weight

In many applications of solar electric generators there is plenty of room for the batteries so this is not a problem. A notable exception is when a Microgenerator is used to power an electronic watch. Here space is at an absolute premium and special batteries fabricated for the application must be used. The silver-zinc battery is widely used for this purpose.

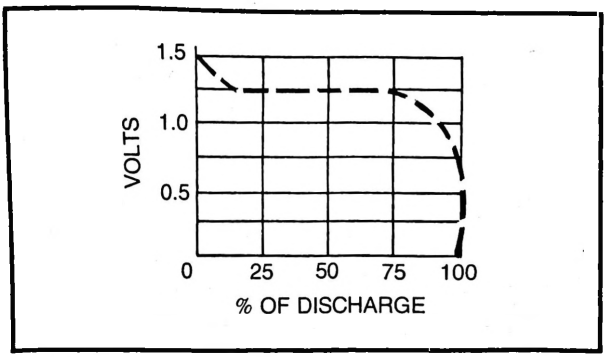


Fig. 5-5. Terminal voltage versus depth of discharge for nicad battery.

Ampere-Hour Capacity

Probably the most important consideration in the selection of a battery for a solar electric generator is the ampere-hour capacity. Simply stated, the battery must have enough ampere-hour capacity to power the load until there is enough sunlight to recharge the battery. In a small application, the situation is often simplified because it is easy to make the battery oversized. Then there will always be enough energy in the battery to operate the load.

In a larger installation where the batteries represent a considerable investment, it is usually worthwhile to make a rather detailed analysis of the requirement so that the investment in batteries will not be higher than necessary.

The ampere-hour capacity of a battery is usually specified together with some standard hour reference such as ten or twenty hours. What this means is that the battery has a certain ampere-hour capacity if it is discharged at a certain rate. If the current drain is lower, the capacity will be somewhat lower. For example, suppose that a battery is rated at 80 ampere-hours and a ten-hour reference is specified. This means that when the battery is fully charged, it will deliver a current of 8 amperes for ten hours. If the current is higher than 8 amperes, the capacity will be somewhat lower. The relationship be-

Table 5-1. Storage Battery Characteristics

TYPE OF BATTERY	VOLTS PER CELL	NOMINAL CAPACITY (A-H)	DEEP DISCHARGE CYCLES	EST LIFE (YEARS)
NiCad, SEALED SINTERED PLATES	1.2	0.2–160	200–2000	2–10
NiCad, SEALED POCKET PLATES	1.2	0.05–70	100–250	5
LEAD ACID SEALED	2.0	0.9–7.5	100–400	4–5
LEAD ACID VENTED	2.0	0.1–120	200–700	3–6
SILVER-ZINC	1.5	0.1–300	1–80	0.02–2

tween the capacity of a battery and the load current can be found in the manufacturer's literature.

The battery field is not static. New types are being developed regularly for different applications. For this reason, no list of specifications and features of various batteries can be complete. A list of some of the more commonly used batteries and their characteristics is given in Table 5-1.

THE COMPLETE SYSTEM

Figure 5-6 shows a diagram of a complete solar electric generator. Note that a diode has been included between the solar cells and the storage battery. The purpose of the diode is

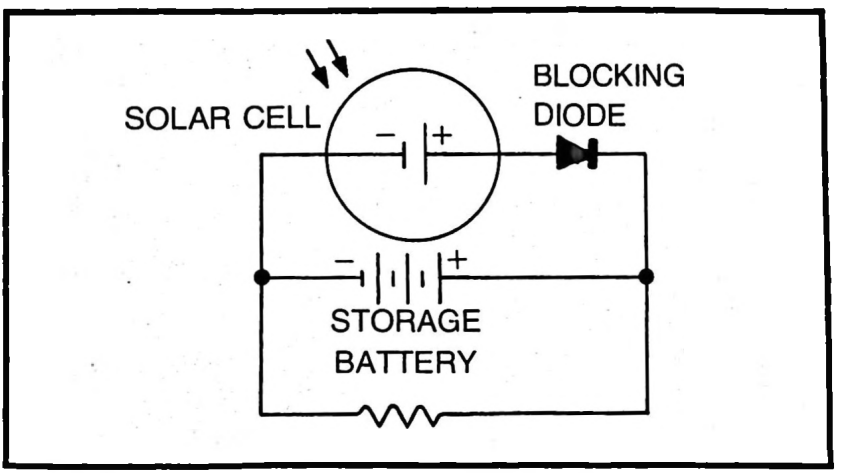


Fig. 5-6. Complete solar electric generator. The diode prevents battery current from flowing through the solar cells when its output is zero.

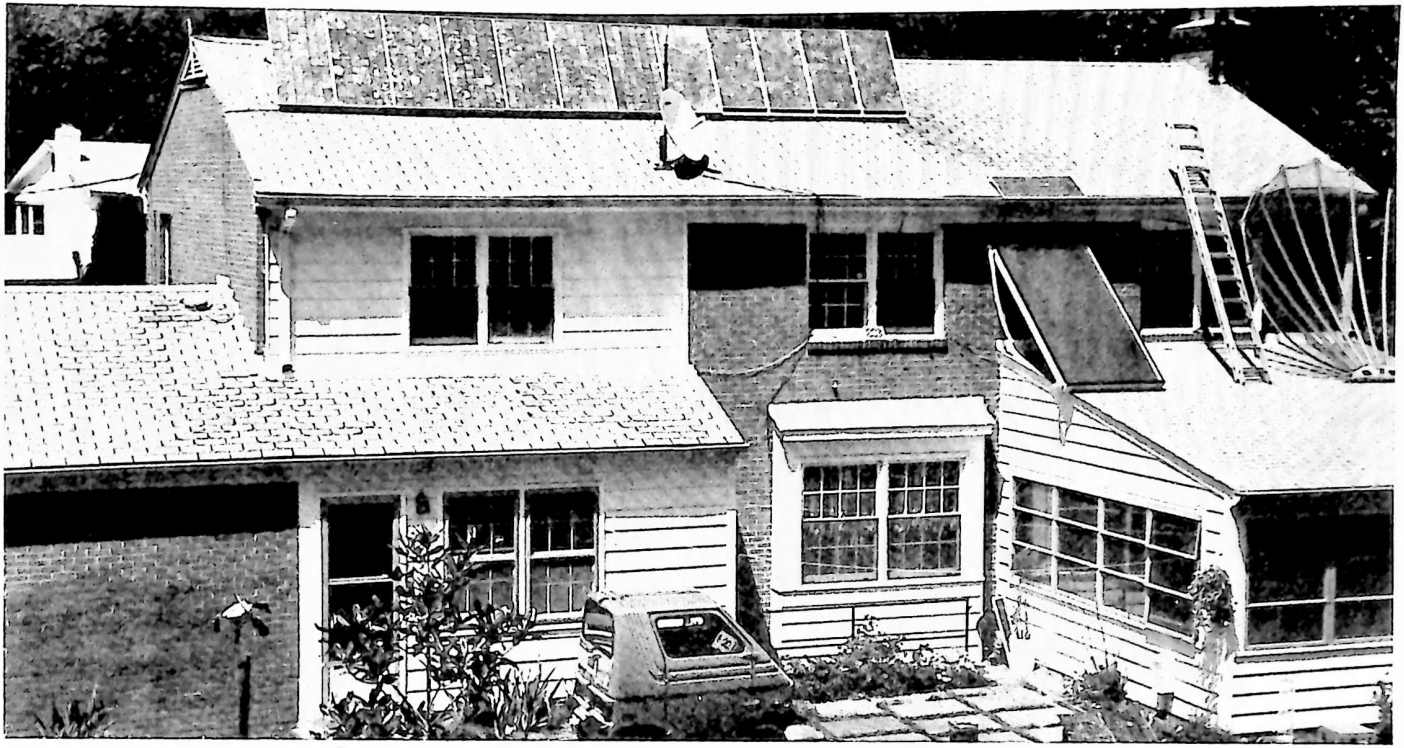


Fig. 5-7. A Solarex twelve-panel photovoltaic system supplies 700 watts under peak sun conditions to power an electric car and provide lighting for the Newberry house in Bethesda, Maryland.

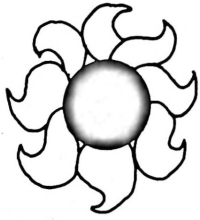
to assure that current will only flow when the solar cell is delivering energy. If the diode were not included, whenever the voltage produced by the solar cell was zero, battery current would flow through the solar cell. This would discharge the battery and might damage the solar cell.

In applications where the solar panel will deliver more energy than is required by the load at any particular time, it is advisable to include a regulator to prevent overcharging of the batteries.

As an example of selecting a battery for a system, suppose that the device that we wished to operate with solar electricity required 12 volts and had an average daily requirement of 10 ampere-hours. Further suppose that the longest period where there would be little sunlight is expected to be one week. To be on the safe side, the batteries should be capable of operating the sytem for a week. We could meet this requirement quite easily by using an 80-ampere-hour automobile battery. If the system were located where the average temperature during part of the year would be very low, it would be advisable to include additional battery capacity.

Chapter 6

Applications of Solar Cells



Originally the solar-electric generator, being comparatively expensive, was used only where other sources of electrical power were not practical. Thus the first significant application of solar cells was in the space program. In fact much of the solar cell development performed under the space program is finding its way into other applications.

Recently, the picture has changed drastically. Whereas the cost of conventional hydrocarbon fuels is rising sharply, the cost of solar-electric generators is actually declining. This, together with the threatened shortage of conventional fuels, is leading to many new applications of solar-electric generators. Solar cells are now used, not only in locations where power lines are not available, but also in many places where they are simply more convenient and reliable. In several applications the solar-electric generator is becoming the most economical source of electric power.

In this chapter we will discuss a few present-day applications of solar cells. The examples have been selected to give an idea of the wide variety of applications of solar cells. The descriptions given here by no means exhaust the possible applications, which seem to be limited only by the ingenuity of the user.

RADIO & TELEVISION

The transmission of radio and television signals depends on the use of an optimum site for the transmitting antenna. The best site is usually the one at the highest possible elevation. Unfortunately, such a site is apt to be one where electric power lines are not available and the transportation of fuel for portable electric generators would be prohibitively expensive.

Much of the two-way radio in use today depends on the use of radio repeaters. A repeater is simply a receiver and transmitter located at some high point overlooking the area of signal coverage. Radio transmitters installed in motor vehicles use small antennas and are often not in good locations. As a result their signals will not propagate over large distances. By using a repeater at a nearly optimum site, the weak signals from the mobile units can be picked up and rebroadcast to provide good coverage over a large area.

In the past, some of the best possible sites for repeaters have been passed up simply because electrical power was not available at the site. In many areas there are hills or mountains that would be ideal repeater sites, but because of the nature of the terrain power lines have never been brought to the area.

An FM or TV translator is very similar to a two-way radio repeater, except that it rebroadcasts radio and TV programs to areas which, because of their geographical location, would otherwise have little or no radio or TV service. The translator usually picks up a signal on one channel and rebroadcasts it on another channel that is not used for broadcasting in the particular area.

As was the case with repeaters, many ideal sites for translators have never been used because of the absence of electrical power lines. Sites have usually been chosen where power lines were available even if the site happened to be far from ideal for reception or transmission of signals. Solar electric generators make it practical to select ideal sites regardless of the availability of power lines.

Solar energy can also be used for powering radio and TV

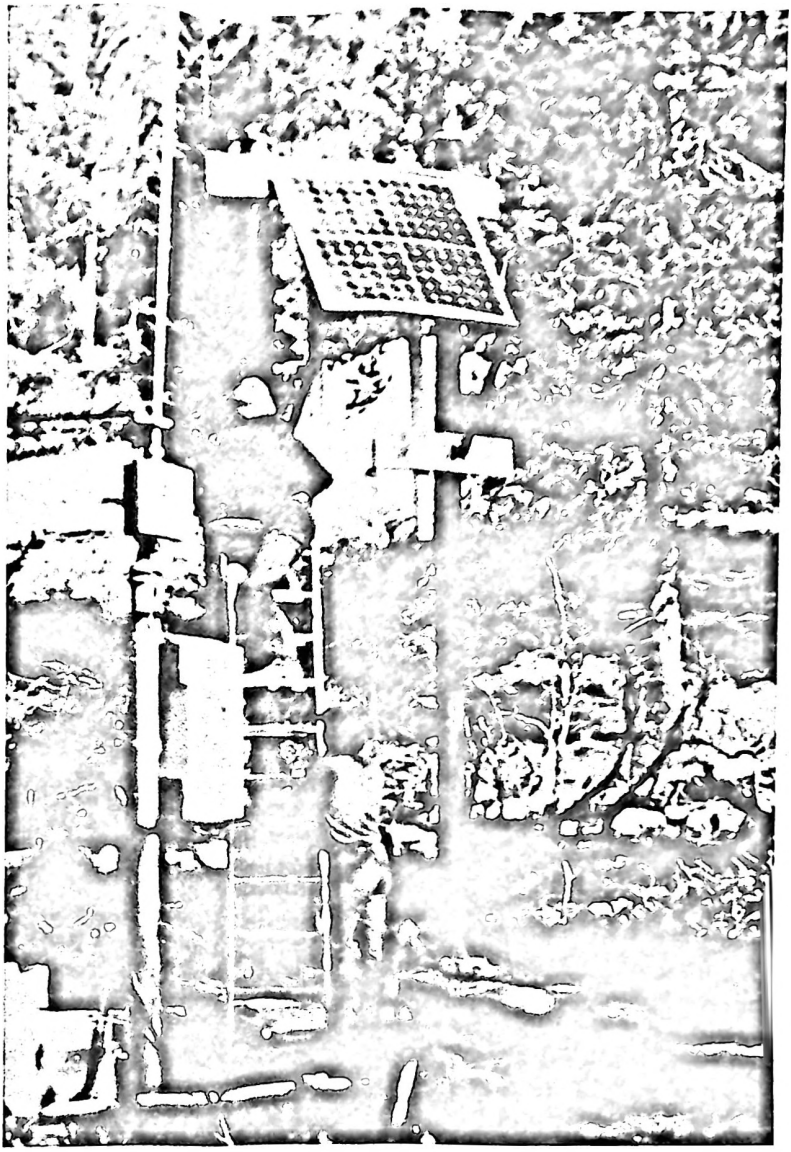


Fig. 6-1. Tourists hear a recorded message powered by the sun when they visit Firehole Lake in the Yellowstone National Park. A 136-watt solar array provides the electricity needed.

receivers. More and more public service announcements of hazardous weather conditions and other emergencies are being made on television broadcast stations. These announcements are of little value if the people affected are without electrical power during the emergency. A solar elec-

tric generator can be used to operate a radio or TV set both to conserve conventional sources of energy and to provide reliable operation during a power outage.

Yet another application where solar cells can improve television reception is in providing operating power for the head end of a cable TV system. The head end of the system is where the signals from distant television stations are picked up for rebroadcast along the cable. As with repeaters and translators, the geographical location of the head end of a cable TV system is very important. Ideally, the head end should be located at the highest practical elevation where the path to the distant stations will be free of obstructions. In the past, the availability of electric power was a prime consideration in the location of the head end. This is no longer a restriction,

Fig. 6-2. Television reception in remote areas such as this in Oman is enhanced by the use of solar electricity in broadcasting and repeater stations. (Photo courtesy of Ecodynamics)

because solar electric generators can be used to supply the operating power.

FIBER OPTICS

Optical fibers are competing increasingly with coaxial cables for the transmission of data, television programs, and telephone conversations. Both fiber optic systems and the conventional coaxial cable require repeater amplifiers at intervals along their length. The coaxial cable has the advantage that operating power for the repeater amplifier can be transmitted along the cable with the signal. The optical fiber, being an insulator, can't get power to the repeater in this way. Thus a power source is required at each repeater amplifier location. This need not be a problem, because small solar electric generators can be used at each repeater location. Figure 6-3 shows a sketch of a fiber optic repeater with a solar electric generator.

AGRICULTURAL APPLICATIONS

There are many places on agricultural installations where solar electric power can be used to advantage. In recent years many different electric and electronic devices have been developed that are revolutionizing all aspects of agriculture. The application of these devices is somewhat limited by the fact that a farm occupies a large area and electrical power is not available over much of the area. Solar electricity makes it possible to use electric and electronic devices at any location where sunlight is available.

A problem frequently encountered in agriculture is that in many areas of the world where there is an abundance of sunshine there is little or no water for irrigation. Crops require both sunshine and water for growth. Solar electricity permits using some of the sunshine that is plentiful to develop electric power for pumping water which is scarce.

Figure 6-4 shows the world's largest application of a solar electric generator to the problem of irrigating an agricultural installation. This system, installed at the U.S. Department of

Agriculture's Mead Field Laboratory in Nebraska, pumps water at the rate of one thousand gallons per minute from an irrigation reservoir for twelve hours every day.

The pumping system, which is driven by a ten horsepower motor, operates on electric power produced by an array of 120,000 individual solar cells. The cells are in the form of Type 9200J Unipanels. This panel is very similar to the Type 4200J which was described in Chapter 5. The array has a peak power rating of 25 killowatts.

Water pumped by the system is distributed throughout the area by means of a system of pipes, part of which is shown in Fig. 6-5.

Farms use many machines, such as tractors and harvesters, that use conventional fuels such as gasoline to power their engines. These machines also use electric batteries to start the engines and power accessories. To conserve fuel, these machines are often left at remote locations, far from a source of electrical power. If the machine isn't used for an extended period of time because of some such factor such as inclement weather, the storage battery will often go dead making it impossible to start the machine.

By installing a small solar electric generator on such a machine, the storage battery can be kept fully charged. The machine can then be started easily, even if it has been left idle for an extended period.

Many farms are located in remote areas where electrical power is not as reliable as in an urban area. Power outages are not infrequent. A solar electric generator will provide a good source of emergency power in such locations. By using solar cells to charge storage batteries, energy will be stored during periods of sunshine for use when power is not available during a storm.

THE CONSTRUCTION INDUSTRY

In many areas, construction of new buildings is started long before electrical power lines are installed to the site. There is the same problem of keeping construction vehicles'

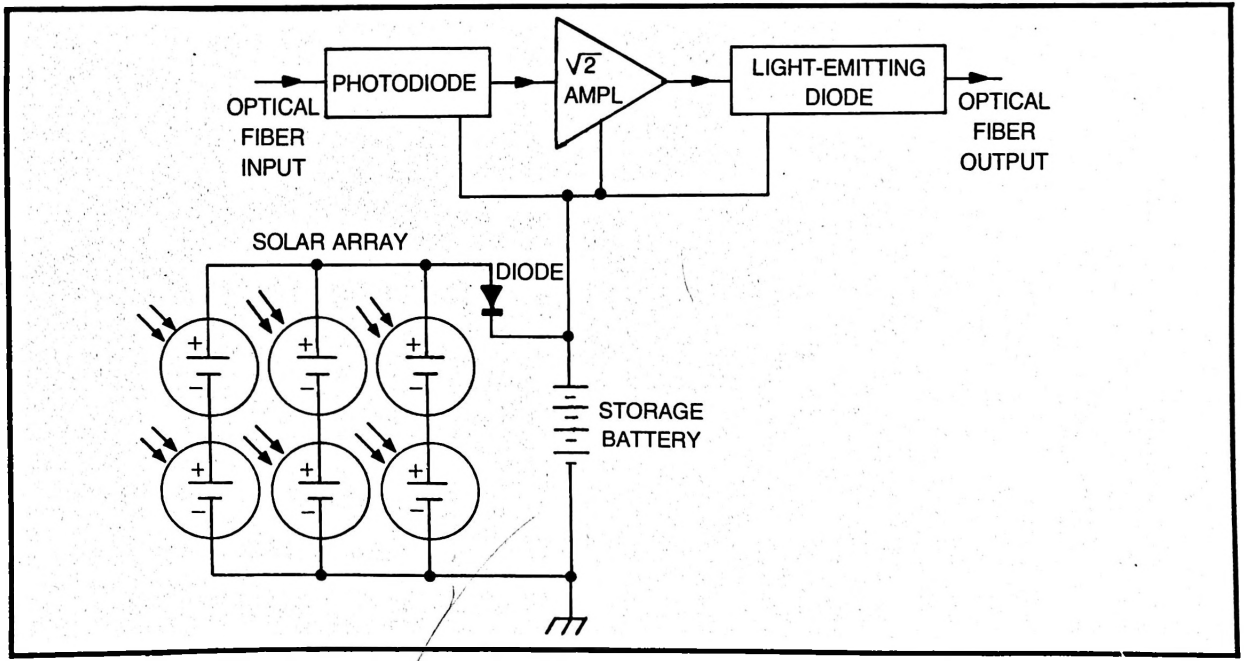


Fig. 6-3. Solar-powered fiber optics repeater.

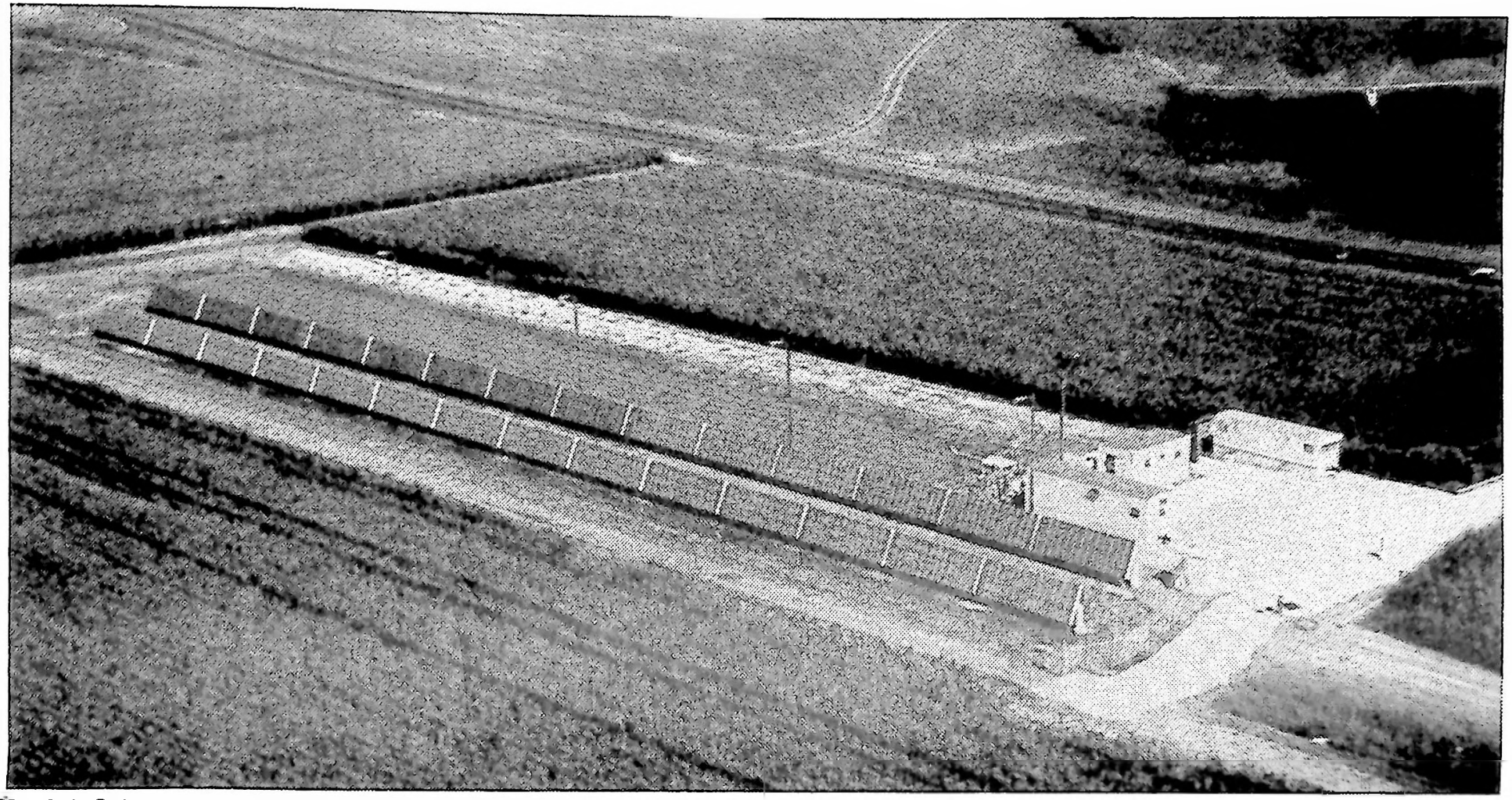


Fig. 6-4. Solar-powered irrigation system in Nebraska.

batteries charged as was mentioned in connection with agriculture in the preceding paragraphs.

This absence of electrical power can seriously hamper construction activities. Often temporary power lines are strung to the site at great expense.

A temporary solar electric generator installed at a construction site can be used to provide electrical power during the construction phase of the project. When the job is completed, the generator can be moved to the next site.

A common use of solar electricity in construction is the solar-powered roadside construction flasher shown in Fig. 6-6.

This device consists of a flashing light, a storage battery, and a small array of solar cells. The cells perform the double duty of keeping the storage battery charged and turning on the flasher when the ambient light falls below a certain level.

REMOTE AREAS

In most urban and suburban areas, electricity is taken for granted. One of the things that has held up the development

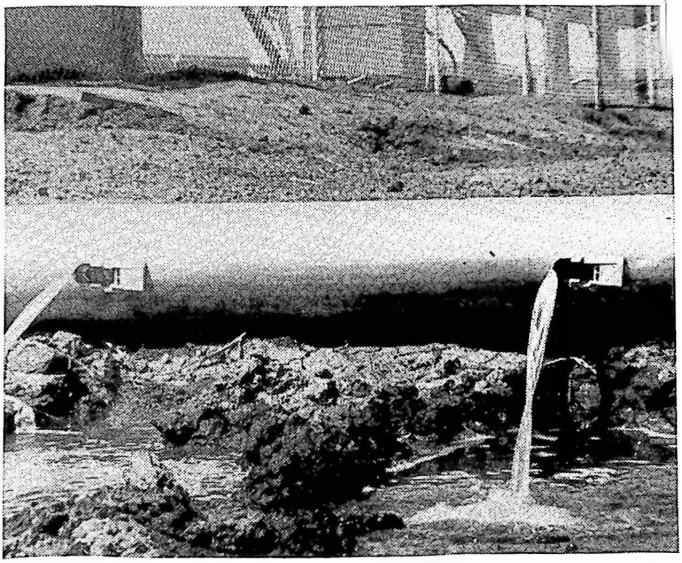


Fig. 6-5. Part of water distribution system of Fig. 6-4.

and utilization of many areas is simply the absence of electrical power. Of course, portable generators driven by hydrocarbon fuels could be, and somtimes are, used at such locations, but there is still the problem of transporting fuel to the site.

There are many places where it is obvious that electric and electronic devices could be used to advantage if electrical power were available. There are other situations, however, where the absence of electrical power has been accepted for so long that the advantages of electrical solutions to problems hasn't even been considered.

A typical example of this type is shown in Fig. 6-7. Here a solar-electric generator is used to power a specially designed flush toilet at a remote site in Custer National Forest. The site is at Rocky Creek Vista Point, a scenic overlook on the Beartooth Highway between Red Lodge, Montana and Yellowstone National Park. It is estimated that nearly 50,000 people visit this spot during the summer months. Until recently, the only sanitary facility at the site was an eight-fixture vault toilet with an 18,000-gallon holding tank. The vault leaked at the rear wall, which was exposed because of the steep slope. The exposed raw sewage was a potential health hazard, and the strong odors detracted esthetically from the site.

Obviously, a different type of sanitation system was desirable, but neither water nor electrical power were available at the site. The cost of running an electrical power line through the rugged terrain would be prohibitive.

A new type of sanitation system that doesn't require water became available. This system operates much like a conventional flush toilet, but uses a colorless liquid similar to mineral oil for flushing. The fluid looks very much like water, but it can be recycled within the system to carry the wastes to a sealed tank. This flush system uses a small pump, driven by a 24-volt DC motor at each fixture to recirculate the fluid.

Inasmuch as there was no electrical power at the site, various ways of supplying operating power for the system were considered. The closest electric power line was nearly

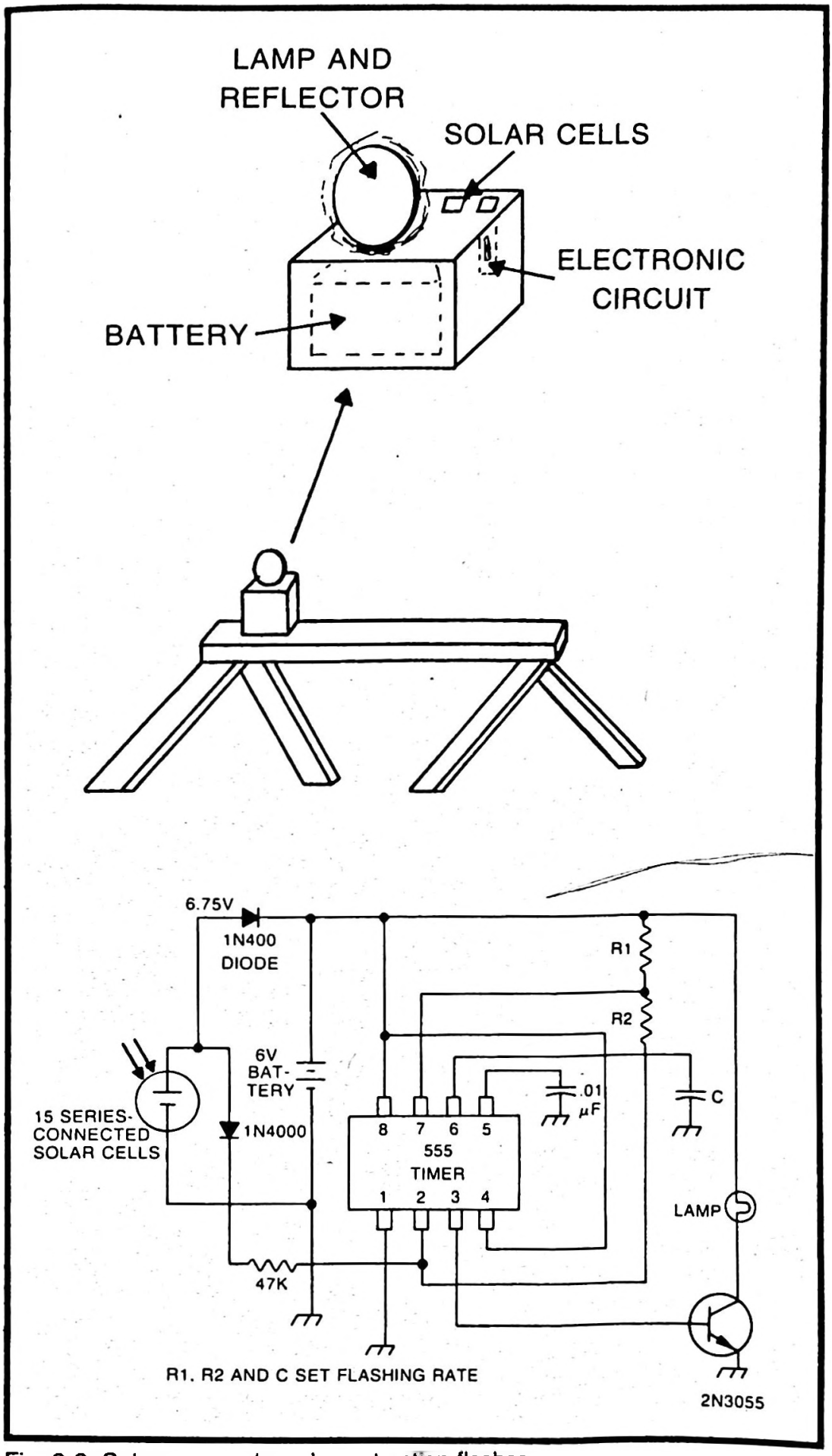


Fig. 6-6. Solar-powered road construction flasher.

two miles away over formidable terrain. Running a power line to the site would cost somewhere between $35,000 and $85,000. Other power sources that were considered included a gasoline generator with automatic starting, a wind-driven generator, and solar electricity.

The storage-battery requirements turned out to be the same for all three of these approaches. A rather detailed analysis was made and solar-electric panels were finally selected because of the low maintenance cost and simplicity of operation.

The complete solar array, mounted on the roof of one of the buildings shown in Fig. 6-7, contains 1664 individual solar cells. It produces 15 amperes at 24 volts—a peak power output of 360 watts. The area of the complete array is 73 square feet.

Additional examples of how photovoltaic installations provide electric power for remote locations are given in Figs. 6-8, 6-9, and 6-10. At the Yellowstone National Park, tourists hear a prerecorded explanatory message that is powered by a solar-electric system. Likewise, both railroad crossing signals and the kind of Coast Guard navigational beacon shown in Fig. 6-9 are ideal applications for low-maintenance, low-cost solar electricity.

While it is often expensive to obtain utility-generated power in many parts of the United States, in some areas of the world it is impossible. In many underdeveloped nations the nearest utility power grid may be hundreds of miles away, and in such areas solar generators may be just about the only answer to the need for electric power. For example, Fig. 6-2 shows a television broadcasting repeater station in a remote area of Oman. Without such stations—which depend on photovoltaics—there would be no television or radio communication in much of the nation.

SOLAR-ELECTRIC CATHODIC PROTECTION

Electrolytic corrosion is one of the major causes of deterioration of all types of metal structures. It has been esti-

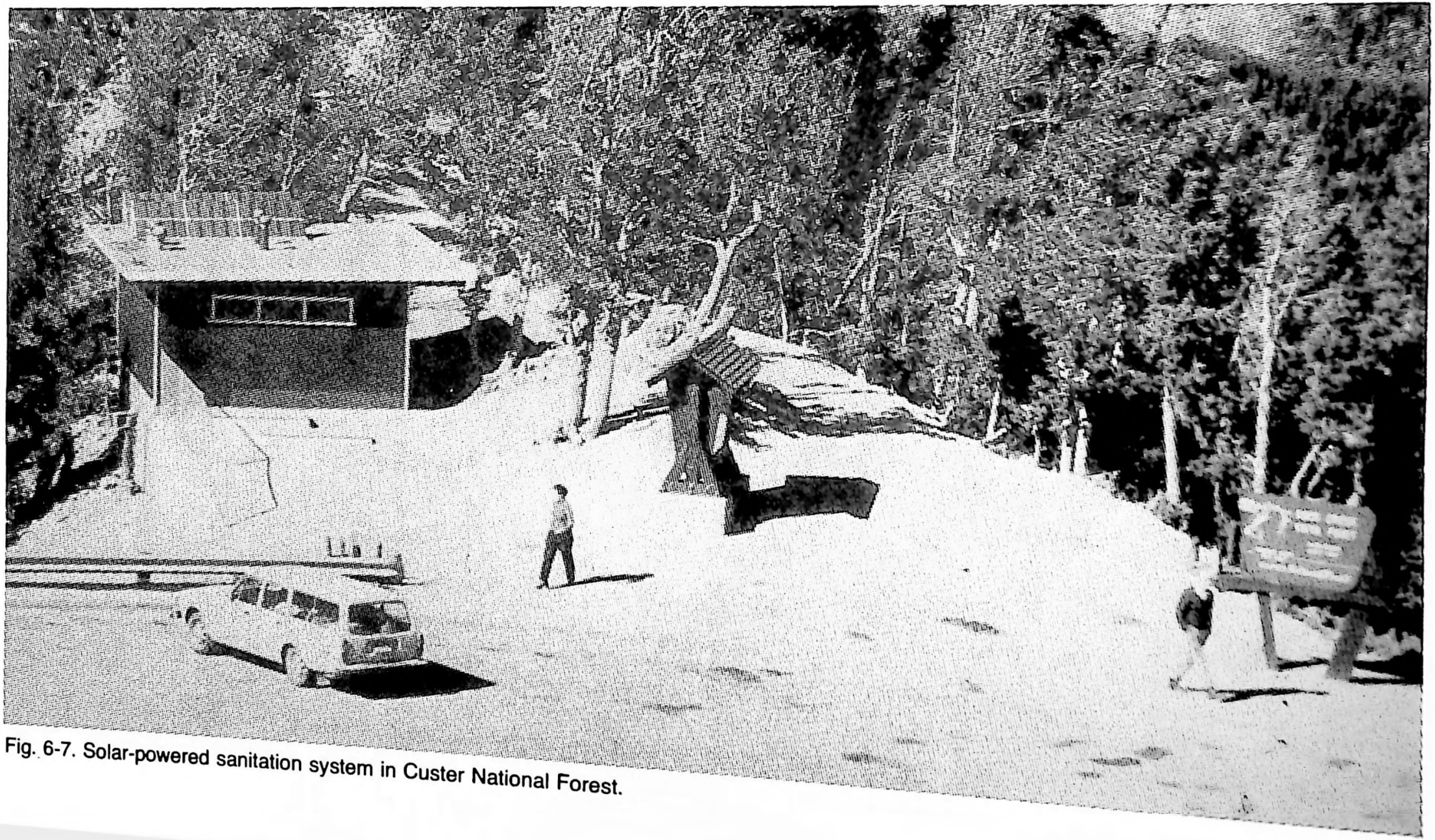


Fig. 6-7. Solar-powered sanitation system in Custer National Forest.

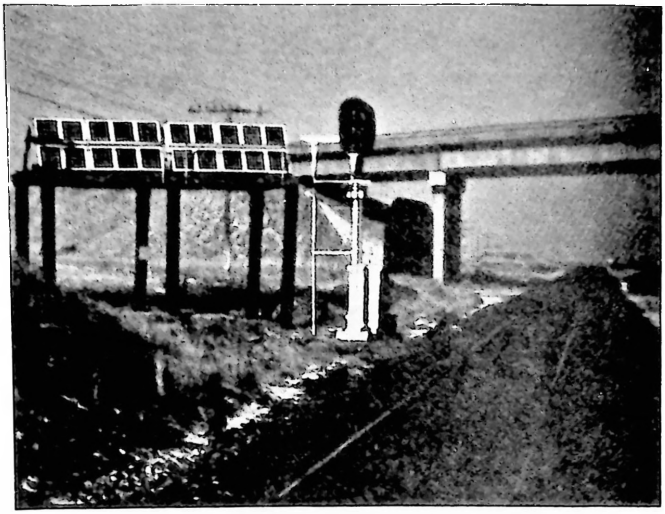


Fig. 6-8. Railroad crossing signals in remote areas in many parts of the United States are powered by no-maintenance solar-powered apparatus like this.

mated that the annual cost of corrosion in the United States is about eight billion dollars.

Electrolytic corrosion can occur whenever we have two dissimilar metals in contact with each other, or connected together electrically, under conditions where the environment may be electrolytic. As shown in Fig. 6-12, one metal will tend to become an anode, and the other a cathode, of what amounts to a small electric battery. Whenever a current can flow from the cathode of this battery to its anode, either through the environment or along the surfaces of the metals, corrosion will occur at the anode. Note that there is no corrosion at the cathode.

Actually, we don't need to have two different types of metal to get electrolytic corrosion. Sometimes, impurities in the same type of metal can make one part behave like an anode and another part like a cathode. The electrolytic currents can eat away a large amount of metal at the anode. For example, a current of 1 ampere will corrode away twenty-two pounds of steel in a year.

One way to protect against electrolytic corrosion is to force an appropriate amount of current to flow through the metal structure in the opposite direction to which corrosion currents would flow. This will make the part of the metal that would otherwise behave like an anode to be a cathode, at

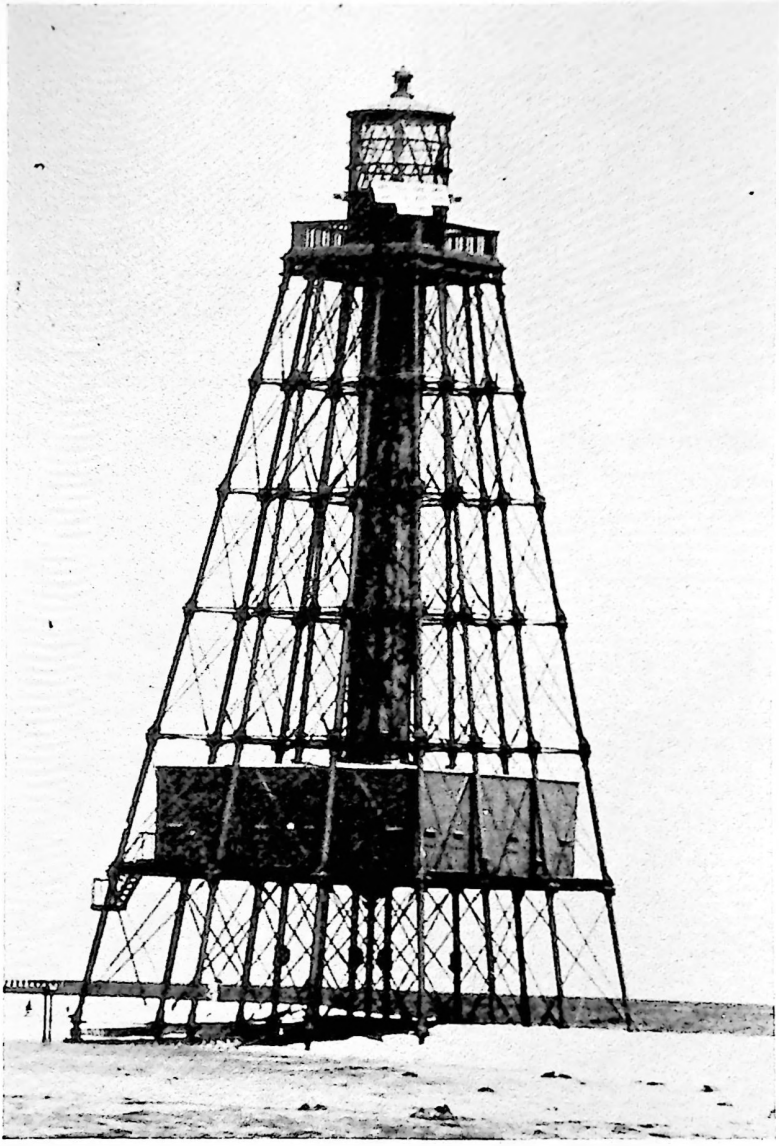


Fig. 6-9. This U.S. Coast Guard reef-warning beacon in Florida is an example of how solar electricity—which demands no fuel, utility power or maintenance—is ideal for remote sites.

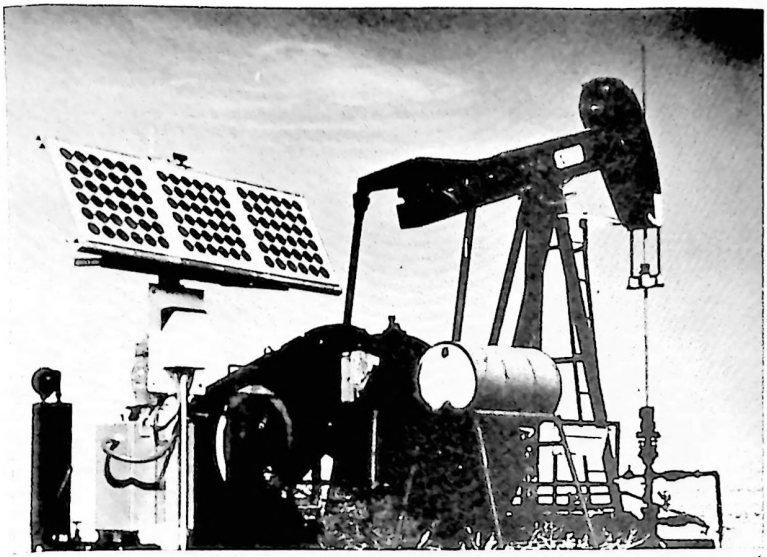


Fig. 6-10. Protection against corrosion is provided by electric current generated by this 60-watt photovoltaic array on a natural-gas wellhead structure.

which no corrosion will take place. Another metal, which we will allow to corrode, can be added to the system to serve as an anode. This other type of metal that is added to the system is

Fig. 6-11. Soldiers in the field can use light, portable solar arrays to power reliable communications even when they are far from the nearest commercial facilities or conventional power sources.

often called a sacrificial electrode because we will allow it to corrode instead of the main structure. This method of protection against electrolytic corrosion is usually called *cathodic protection*. The method requires a source of electrical energy which can quite conveniently be a solar-electric generator.

One of the first applications of solar electricity to cathodic protection was made under the sponsorship of the U.S. Department of Transportation on a bridge near Washington, D.C. in 1976. This system is in use on the Dear Run Bridge on

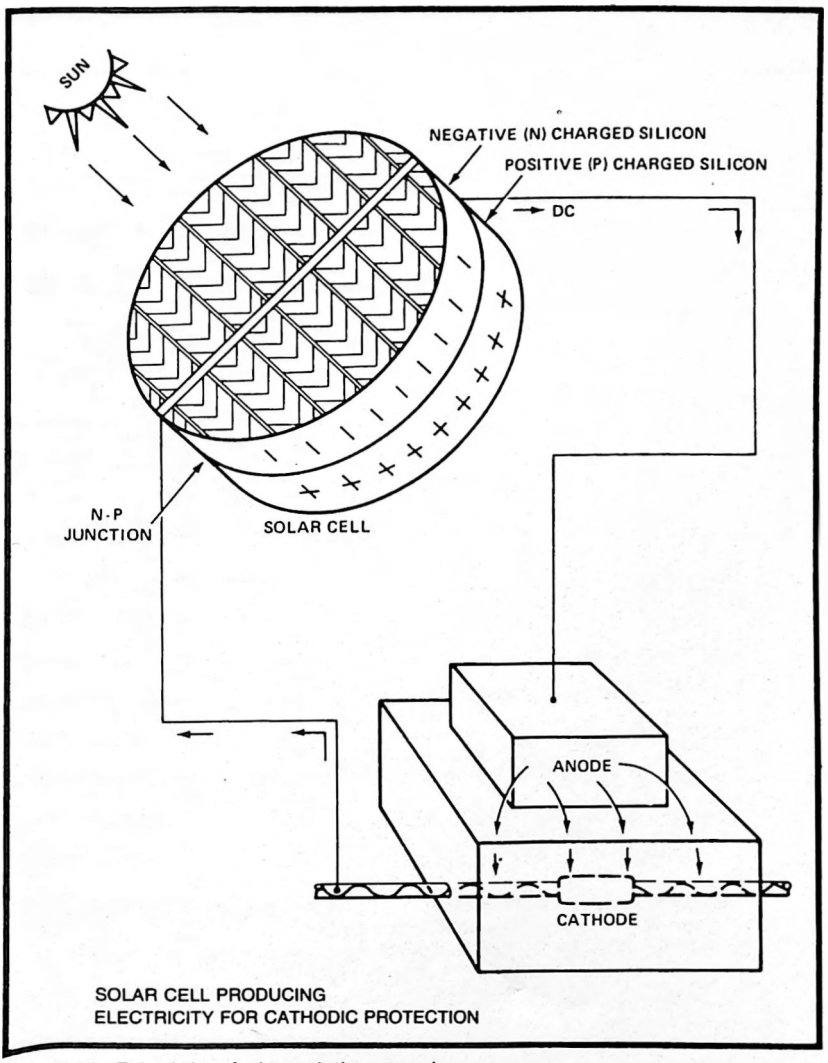


Fig. 6-12. Principle of electrolytic corrosion.

the George Washington Memorial Parkway. Solar electricity was selected as a power source because the initial cost was $4,620 as compared to the proposed cost of $13,954 for using commercial power. In addition, with the solar system there is no monthly charge for electricity.

An analysis of the structure showed that a continuous direct current of 6 amperes at 2 volts would be required to provide cathodic protection. A study of the weather data in the Washington, D. C. area showed that in order to get a continuous 6-ampere current twenty-four hours a day, a peak current of 33 amperes would be required. Figure 6-13 shows a sketch

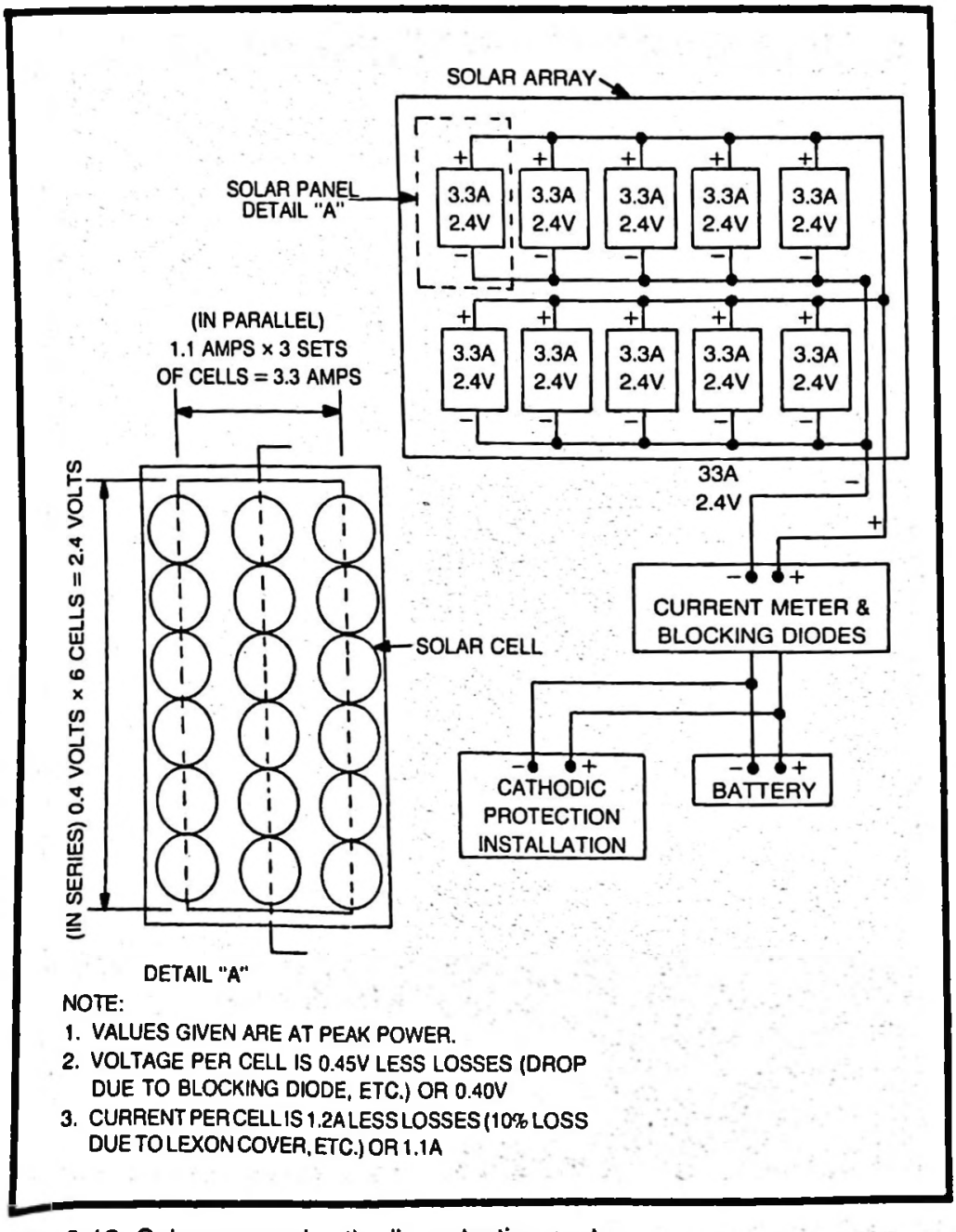

SOLAR ARRAY
SOLAR PANEL DETAIL "A"
3.3A 2.4V
(IN PARALLEL)
1.1 AMPS × 3 SETS OF CELLS = 3.3 AMPS
33A 2.4V
CURRENT METER & BLOCKING DIODES
SOLAR CELL
CATHODIC PROTECTION INSTALLATION
BATTERY
(IN SERIES) 0.4 VOLTS × 6 CELLS = 2.4 VOLTS
DETAIL "A"
NOTE:
1. VALUES GIVEN ARE AT PEAK POWER.
2. VOLTAGE PER CELL IS 0.45V LESS LOSSES (DROP DUE TO BLOCKING DIODE, ETC.) OR 0.40V
3. CURRENT PER CELL IS 1.2A LESS LOSSES (10% LOSS DUE TO LEXON COVER, ETC.) OR 1.1A

Fig. 6-13. Solar-powered cathodic protection system.

of the system. Energy from the solar array charges a bank of batteries which in turn furnish current to the electrodes of the protection system. The usual blocking diode is provided to prevent the batteries from discharging through the solar cells during the night. In this application, no charge-limiting system was required. The amount of sunlight was not great enough to overcharge the batteries during periods of sunlight.

The storage battery selected has a capacity of 2016 ampere-hours. It is expected that the only maintenance required by the system will be adding water to the battery once every two or three years.

The solar-electric generator selected for this application consists of ten panels connected to provide the required 33 amperes of peak current. The nominal voltage output of the array is 2.4 volts, which is high enough to allow efficient charging of the 2-volt battery.

APPLICATIONS OF CONCENTRATOR CELLS

The concentrator cell described in Chapter 4 not only reduces the number of cells required for a given power output, but also increases the efficiency of the array and reduces the cost per watt of electrical power. The fact that thermal energy can also be derived from the array further increases the overall energy conversion efficiency of the system.

One of the largest applications of concentrator cells is at Mississippi County Community College (Fig. 6-14) in Blytheville, Arkansas. This installation, funded by the U.S. Department of Energy, contains more than 50,000 concentrator cells encapsulated in nearly 300 solar modules. The system provides approximately 362 kilowatts of peak power and supplies energy for new solar-powered classroom facilities.

MILITARY APPLICATIONS

The armed forces are the largest users of electronic equipment and are always in need of reliable sources of electrical power. The most obvious need is at battle sites where conventional power lines may not be available or may have

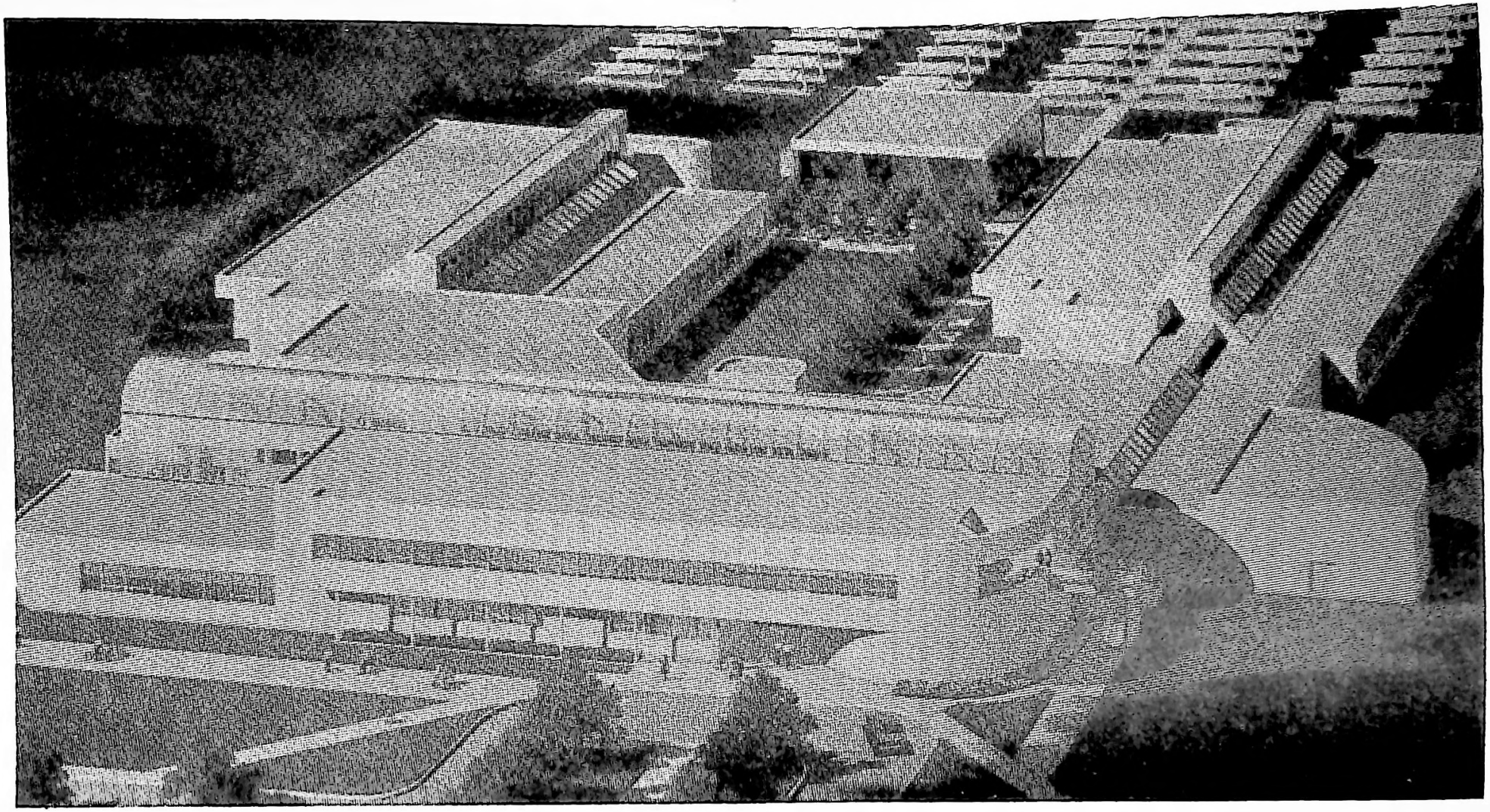


Fig. 6-14. One of the largest installations of solar concentrators located at Mississippi County Community College in Blytheville, Arkansas.

been destroyed. The logistics problems of transporting fuel for portable generators to such sites are often severe.

A less obvious need for power is for testing facilities, where tests of armament are necessarily carried out at remote locations. The cost of running power lines to some of these testing sites is prohibitively high. Solar-electric generators provide a reliable source of power that can be used to recharge batteries and reduce the need for fuel for powering portable electric generators.

Figure 6-15 shows a solar-electric generator installed at Luke Air Force Base in Arizona. This system supplies operating power to a TV camera and its associated equipment used as a part of the Television Optical Scoring System (TOSS). This system is used to evaluate the performance of weapons systems. Because the system is self-contained, it can be mounted very close to the range. No regular operating or maintenance attention is required, so there is no need for protective bunkers for operating personnel.

MICROGENERATOR APPLICATIONS

Normally, when we think about the most expensive applications of electric power, we think of installations that use huge amounts of power, such as aluminum refineries. Actually, although such installations use large amounts of energy, the cost per kilowatt-hour is usually very low. The applications where the cost of electrical energy is inconceivably high is with very small devices that use minute amounts of energy. A good example is the electronic watch.

If the battery used in an electronic watch should cost about $1.00, the cost of the actual energy supplied by the battery would be about $4764.00 per kilowatt-hour. This compares with the regular electric utility charge of a few cents per kilowatt-hour of energy.

In spite of the efforts of the designers of batteries for such things as electronic watches, the life of the battery is often less than a year. In an effort to reduce the cost and improve the life of watch power supplies, many manufacturers

Fig. 6-15. Solar cells power military range instrumentation system.

are using or planning to use solar-electric generators in connection with a rechargeable battery to power electronic watches. By using a Microgenerator with one of the newer silver-oxide batteries, a life span of five years or greater can be obtained. Figure 6-16 shows a typical circuit.

The small electronic calculator, although usually not as small as an electronic watch, has a similar power supply problem. Advances in electronics have made it possible to reduce the size of the calculator continually. As the calculator becomes smaller, the battery is apt to become the weakest link in the system. If the battery size is continually reduced, the battery capacity and hence the life of the battery will also be reduced. The solar Microgenerator array is an ideal power source for devices of this type. It can be used to recharge a storage battery, or as we will see in the following paragraph, to operate the calculator without any battery at all.

The Microgenerator is designed to have very good energy conversion efficiency at both high and low light levels. As a result of its low light level efficiency, it can provide enough energy to operate a calculator when illuminated by ordinary room light.

Figure 6-17 shows the world's first solar-powered electronic calculator. Using low current drain liquid crystal display

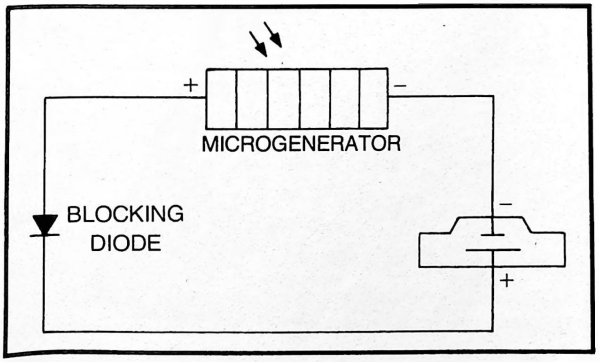


Fig. 6-16. Microgenerator battery charging circuit.

units, and a high efficiency Microgenerator as a power source, this calculator doesn't have any battery at all. Neither does it have an on-off switch. When the calculator is subject to enough light to enable the user to read the display, the miniature solar-electric generator will provide enough energy for its operation.

There is no need at all for an on-off switch—an item that is subject to wear, and hence to failure—because there is no battery to run down. The calculator will be energized whenever light falls on it, but this is no problem. All of the solid-state components have long lives.

There are many other potential applications of the Microgenerator in electronic devices. Many small instruments are being developed for medical applications. Most of these have to be plugged into a charger periodically to keep the batteries charged. The combination of MOS solid-state technology and liquid crystal readout devices make it possible for such devices to have a very low power drain. Thus they are suitable for use with miniature solar electric generators as power sources.

SOLAR-POWERED FLASHLIGHT

Lighting devices that are only used at night are ideal

Fig. 6-17. Calculator powered by solar cells has no battery.

candidates for solar electric power. During the daytime when the device isn't being used, its batteries can be recharged by solar electricity. A device of this type is the solar-powered flashlight shown in Fig. 6-18.

The solar-powered flashlight looks like any other flashlight except that it has a plug in the back for connecting the solar cell. The batteries are rechargeable, rather than the usual flashlight batteries. When the flashlight isn't being used during the daylight hours, the solar cell is plugged in and recharges the batteries. This not only avoids the inconvenient situation where the flashlight batteries go dead, but it eliminates the expense of replacement batteries.

SOLAR-POWERED ATTIC FAN

The solar-powered attic fan, shown in Fig. 6-19, is an example of the application of solar electricity to a device that usually only operates when the sun is shining. Usually an attic fan is operated when the sun is shining brightly heating the attic. At night, when there is no sunlight, the fan is usually turned off.

The fan shown in Fig. 6-19 is driven by a 4-volt solar panel that furnishes 6 peak watts. It can deliver about 250 cubic feet of air per minute. Inasmuch as it is only operates when the sun is shining, there is no storage battery.

SOLAR POWER FOR RECREATION

Many recreational activities, such as golf, hunting, and boating, involve the use of large areas of land or water. Providing electric power lines to such large areas is always expensive, and sometimes impossible. Here again, solar electricity can come to the rescue and make it practical to use electrical or electronic devices at almost any location.

One of the earliest applications of solar electricity to a recreational activity was in the solar-powered electric golf cart. A solar-electric generator mounted on the golf cart not only keeps the batteries charged, it eliminates the need to run power lines to any location where the golf carts might be stored when not in use.

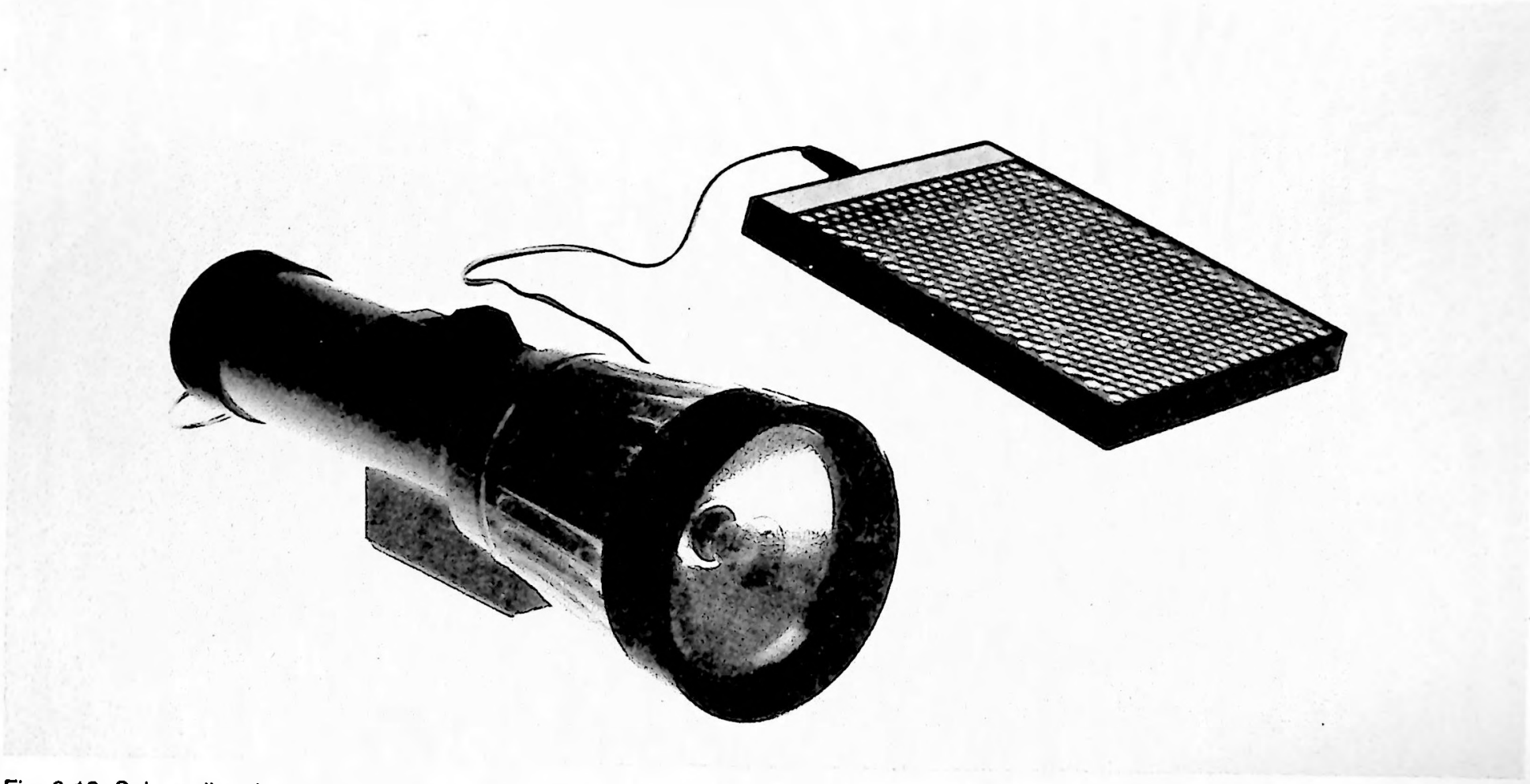


Fig. 6-18. Solar cell recharges flashlight battery.

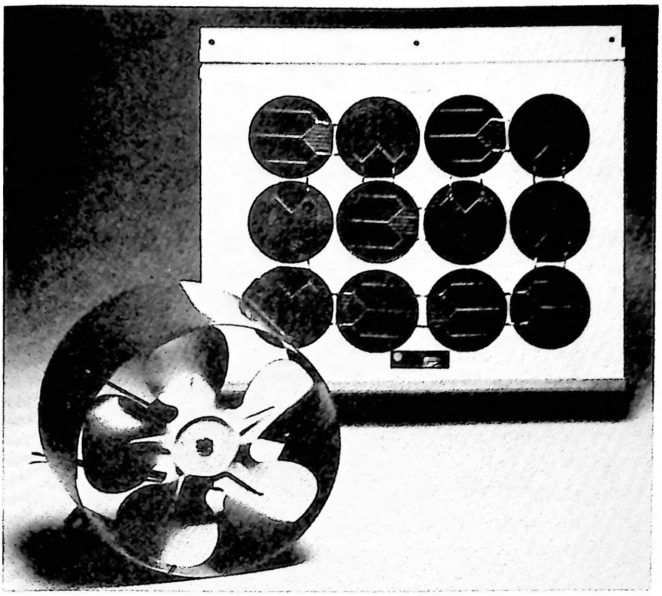


Fig. 6-19. Solar-powered attic fan with remote solar panel.

Hunting lodges are necessarily located in remote locations close to the game being hunted. The operator of such a lodge is faced with the alternatives of going to great expense to provide electric power, either by means of power lines or portable generators, or letting his guests do without the convenience of electric and electronic devices. This situation can be alleviated by the use of solar electric power.

A solar-electric generator mounted on the roof of a cabin

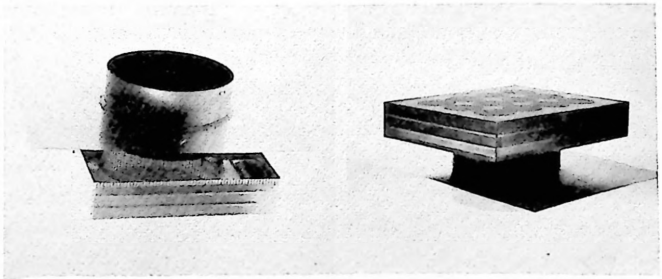


Fig. 6-20. Solar-powered attic fan (inverted at left) with built-in panel.

can provide operating power for radios, television sets, refrigerators, water pumps, attic fans, and a host of other conveniences and luxuries.

Another example of the application of solar electricity to recreational activities is the solar-powered battery charger designed for marine applications. On power boats, an important consideration is conserving on-board fuel. Recharging of batteries from the boat's engine consumes fuel. Many sailboats and yachts have little if any auxiliary power, hence no source of electrical power.

There are many electrical and electronic devices that can be used on boats, not only as conveniences, but as safety devices. The use of a solar-electric generator makes it possible to operate these devices without spending any of the on-board fuel. Most boating is done during daylight hours when plenty of sunlight is available. This assumes that the batteries will be fully charged when the sun sets. Thus the supply can be used to operate running lights, a bilge pump, two-way radio, and other electronic gear.

The solar Energizer® designed for marine applications weighs only four pounds and provides 0.6 amperes of current in full sunlight. In the average United States location it will develop about 18 ampere-hours each week. The charger is designed to work with the standard 12-volt system used on boats.

FUTURE APPLICATIONS OF SOLAR ELECTRICITY

The examples of practical applications of solar electricity given in this chapter are not complete. We have merely tried to give some idea of the many ways in which solar electricity is being used today.

The future applications of solar-electric generators is almost unlimited. With each new technological advance the cost of solar cells drops making other applications economically feasible. In addition to the normal advance in the state-of-the-art, a great deal of effort is being expended toward completely automated production of solar cells that will further reduce the cost.

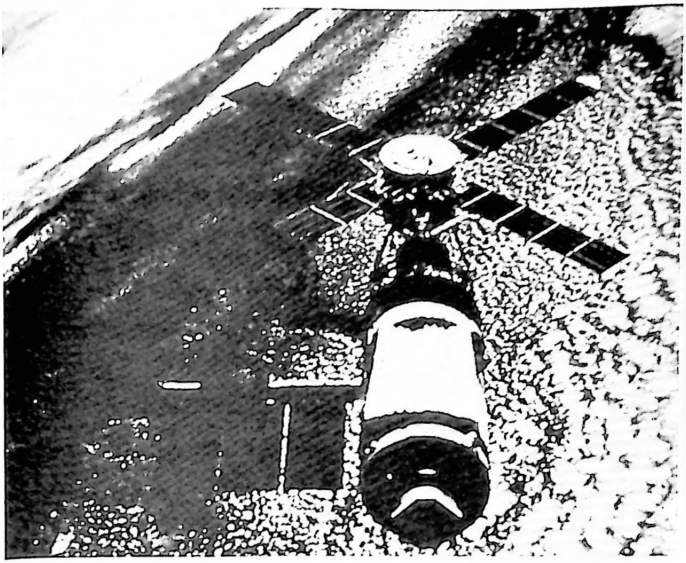


Fig. 6-21. Skylab in orbit. The space program, which provided the initial impetus for the development of photovoltaics, still creates a demand for sophisticated, reliable solar-electric devices. Because they require no fuel, no oxygen for combustion, and no maintenance, solar-electric arrays are ideal for spacecraft.

As we stated earlier, the goal of the U.S. Department of Energy is to reduce the cost of solar cells to less than $0.50 by 1986. Even if this goal isn't completely realized, the cost will continue to decline. This will make solar electricity the most economical approach to electric power in an ever-increasing number of applications.

TWO-WAY COMMUNICATIONS

The use of solar cells to generate electricity at remote mountaintop locations to power two-way communications gear is expanding. Figure 6-22 shows a power-generating system in use atop a New Hampshire mountain, providing electricity from the sun for a two-way radio repeater.

On top of Mount Cardigan, west of Newfound Lake, a solar-electric generator is being used to power a General Electric UHF solid-state radio repeater for the Department of Public Works and Highways of the State of New Hampshire.

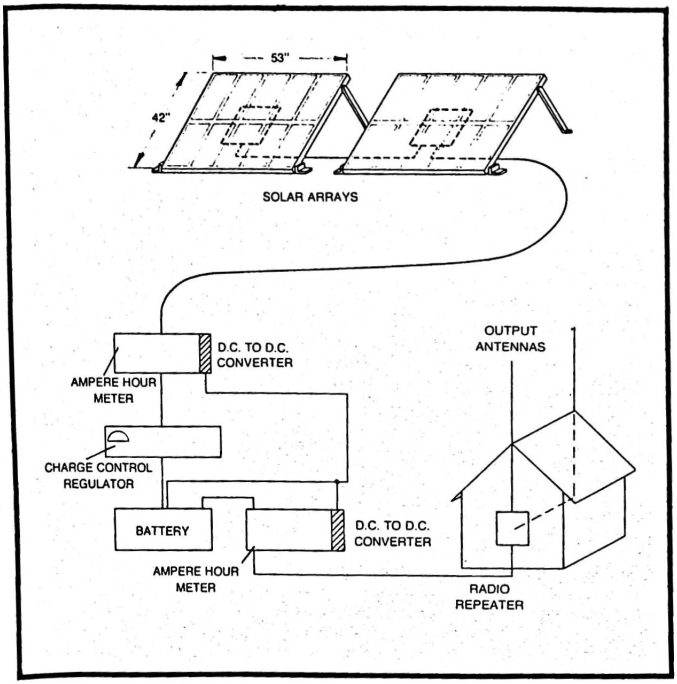


Fig. 6-22. Repeater pictorial block diagram.

The repeater gives line-of-sight transmission and reception for radio contact with units in the New Hampshire valleys. Radio signals from low-powered mobile and portable radios arrive at the repeater where they are boosted and rebroadcast over a wide area to other mobile, portable and base stations. Patrol vehicles use the repeater to communicate with six base stations and 50 other vehicles. The repeater is at an altitude of 3200 feet, atop the mountain, which lets it "see" down into many valleys.

The repeater uses no commercial electrical mains and provides radio cover of 800 square miles.

The power-from-the-sun generating system consists of three parts: a solar panel array, a Solarex Powermizer charge-control circuit, and storage batteries. The solar panels receive sunlight and generate electricity. That electricity is

stored in the batteries which are under control of the Powermizer.

When the repeater is not actually retransmitting a signal, but is listening, it draws 300 mA of current from the batteries. When it is transmitting, it uses 24 amps of current. It runs on 12 volts DC.

The repeater averages about 15 percent transmitting time and 85 percent listening time during the normal eight-hour work day, five days a week. It operates year round.

The solar panels provide 200 watts peak power or 13 amps at 14 volts DC in full sunlight. The batteries are 1008 ampere-hour lead-calcium photovoltaic storage units.

The system was designed for heaviest use in winter time when the amount of daily sunlight is lowest. Extra power is produced in the summer so the Forest Service uses the repeater for fire detection, also. If the Forest Service did not use the extra power, it would be dumped as waste.

In another sun-powered communications system, the SNOTEL environmental data communications system operated by Western Union for the Soil Conservation Service, U.S. Department of Agriculture, is on the air in Idaho.

SNOTEL includes 500 remote monitoring stations, each powered by a battery pack charged by solar panels. The stations are in remote locations where sun power frees them of dependence on power lines. One site is near Moore's Creek Summit in Idaho, powered by a solar panel atop a tower.

SNOTEL relies on reflection of radio waves from electrons in meteor trails to transmit data from remote stations to

Table 6-1. Characteristics: 435HP Unipanel.

Watts (peak)[1]	6
Amps at 14V nominal (typical)	.42
Ah/Week[2]	9.5
Wh/Week[2]	135.0
Voltage at peak power[3]	14.0 nom.
V_{oc}[3]	14.0 nom.

base stations separated by as much as 1200 miles. Since meteor trails exist only from a few thousandths of one second to a few seconds of time, a "burst" type of transmission is used.

Each base station surveys the atmosphere for meteor trails capable of reflecting signals to remote sites. When a suitable path is found, the base sends a signal to one or more remotes which then are triggered to transmit back to the base whatever data the remote site has collected and stored. Each remote unit has 16 sensors of environmental data such as snow depth, temperature, stream flow, and wind velocity and direction. Figure 6-23 shows the SNOTEL meteor burst communications system.

Typical remote sites use 20 mA of current at 12 volts DC on average. The solar panels and storage batteries are beefed up to provide enough backup for extended periods of inclement weather. Table 6-1 shows electrical characteristics of the Solarex Corp. solar panel used.

The 435HP Solarex Unipanel is made up of 36 silicon

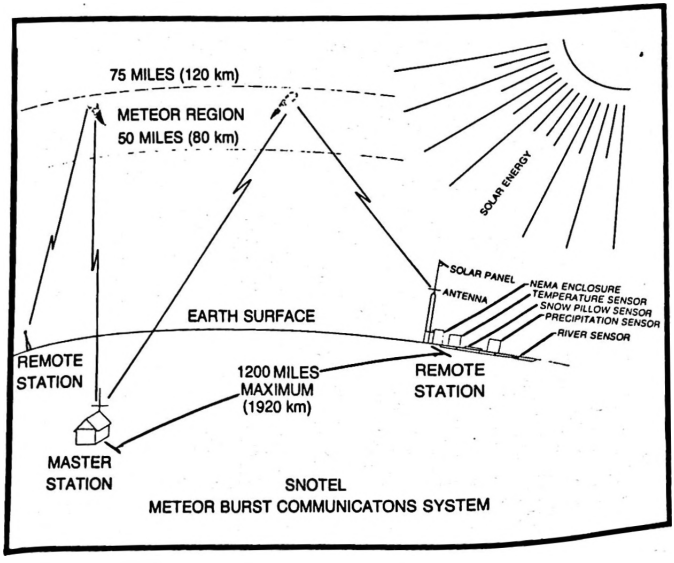
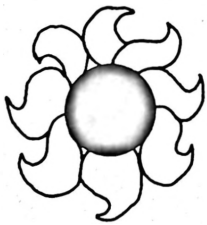


Fig. 6-23. SNOTEL meteor burst communications system.

solar half-cells in series mounted on a fiberglass board in a special stabilized silicone rubber which provides a transparent, weather-resistant, and corrosion-free encapsulation. The cells feature a tantalum oxide anti-reflective coating and redundant collector pattern for high conversion efficiency, and corrosion-resistant electrodes. The shunt regulator is heat-sinked to avoid overheating, and each panel is carefully quality-controlled and tested in house. The 435HP measures 10-⅜″ × 12½″ × ¾″ and weighs 4½ pounds. Other tested applications of the 435 HP include remote telemetry units for oils and gas pipelines, supervisory control and alarm systems, navigation aids, and hydrological and meteorological data collection stations.

Chapter 7
Solar-Electric Projects



The silicon solar cell is one of the most fascinating devices available to the educator or experimenter. All of the components required for solar-electric experiments are readily available at low cost. The circuits involved are much simpler than most other electronic circuits. All solar-cell experiments are educational and many result in useful devices.

The number of things that can be powered by solar electricity is limited almost entirely by the imagination and ingenuity of the experimenter. Many new electronic components operate on very small amounts of power and can be powered with only a few solar cells at most. In this chapter we will describe a few projects that can be performed with a minimum number of components. Projects range from demonstrations of solar energy to providing operating power for small devices.

DEMONSTRATION PROJECTS

Projects that demonstrate solar electricity are fascinating and are of value either educationally, esthetically, or merely as conversation pieces. Used in schools, they will stimulate students interest in science and increase their awareness of the importance of new energy sources.

An excellent device for demonstrating solar electricity is the solar fan cube shown in Fig. 7-1. This 3¾-inch cube is constructed of transparent plastic and contains a solar cell connected to a motor driven fan. Whenever the solar cell is illuminated, the fan will rotate, providing an excellent demonstration of the energy available in sunlight.

The motor and connecting wires are available in different colors to enhance the appearance of the device.

COMPONENTS

All of the components needed for solar cell experiments are readily available. Many popular sizes of solar cells, including Microgenerators, are now available in blister packs. The experimenter can select the size of cell best suited to the projects he has planned.

A word of caution is in order regarding the handling of solar cells. Although solar panels that are packaged for application are rugged and almost indestructible, individual solar cells are fragile devices. The average solar cell is very thin and can easily be broken with rough handling. The surface can become dirty thus reducing its energy conversion efficiency. As a general rule the solar cell should be handled just like any other delicate device such as a lens. Care should be taken not to subject it to shock or stress until it is mounted on some firm support. Once the solar cell is mounted on a solid surface, it will withstand ordinary handling with no adverse effects.

The individual solar cell usually doesn't have any leads attached to it, and the experimenter will have to solder leads. The positive lead is soldered to the back of the cell and the negative lead is soldered to the metallized surface on the front. Excess heat can very easily damage the cell. Only small wire, AWG #26 or smaller, should be used. Use a very small soldering iron, and do not apply heat any longer than necessary to make a good connection.

As explained in earlier chapters of this book, the individual solar cells can be connected in series to get the desired

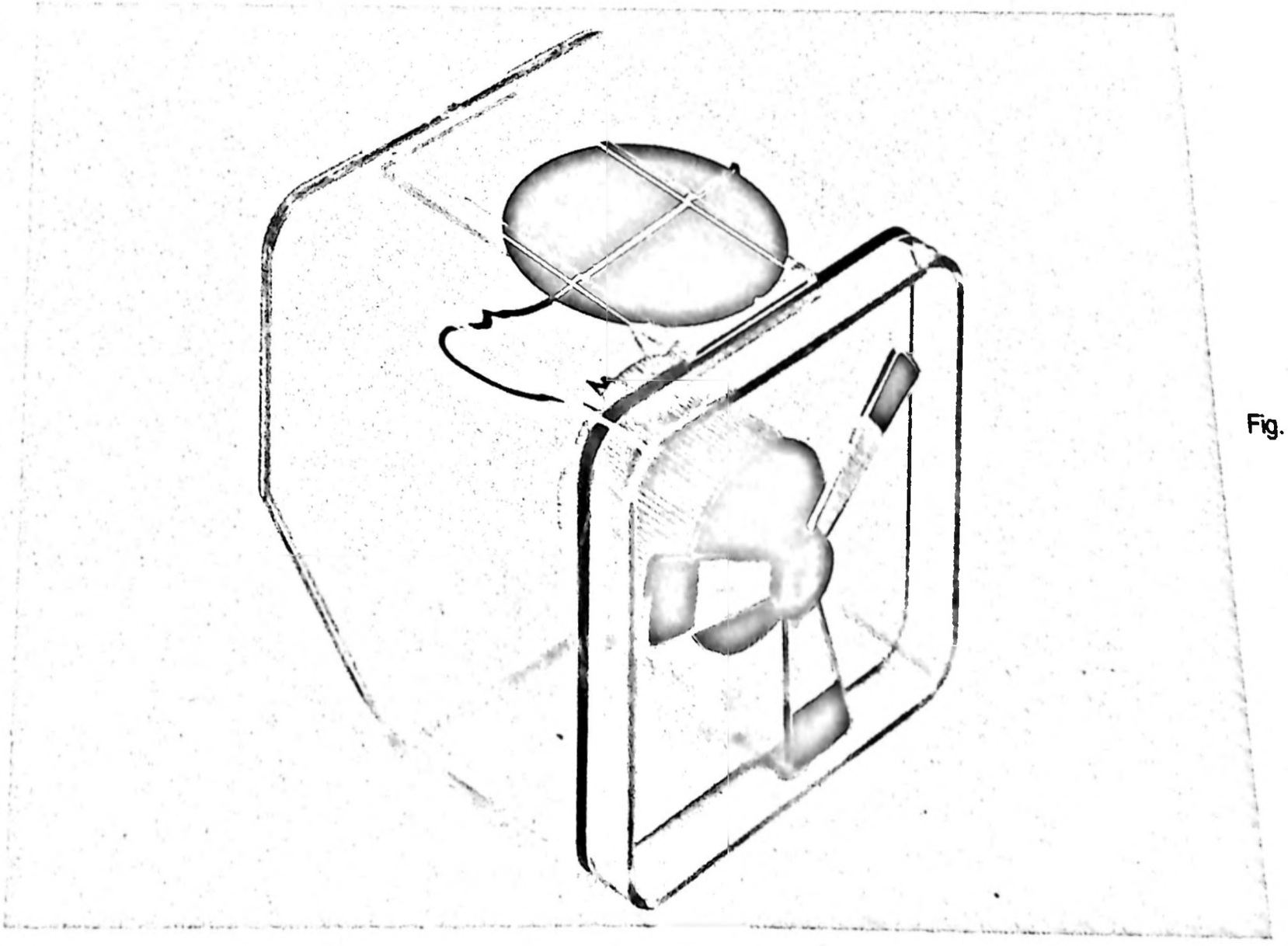


Fig. 7-1. Solar fan cube.

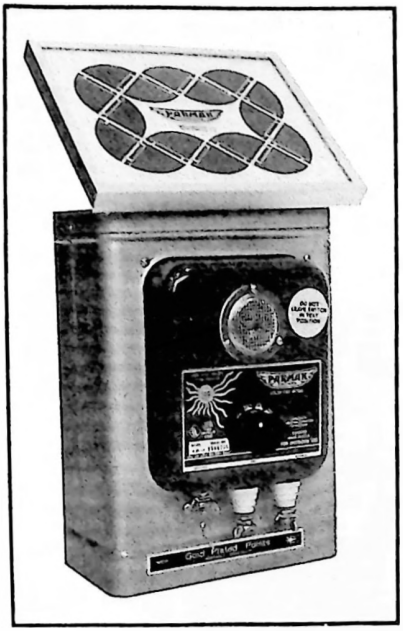


Fig. 7-2. Using sunlight as its power source, this 6-volt electric fencer can charge up to 25 miles of fence with no recharging or battery replacement needed. It can work up to 21 days without sun!

voltage and in parallel to get the desired current. In most applications other than very small ones, cells will be connected in both series and parallel.

A very convenient source of components for many experiments and demonstrations is the Photovoltaic demonstration kit shown in Fig. 7-5. The kit contains nineteen different component parts that can be interconnected in many ways to

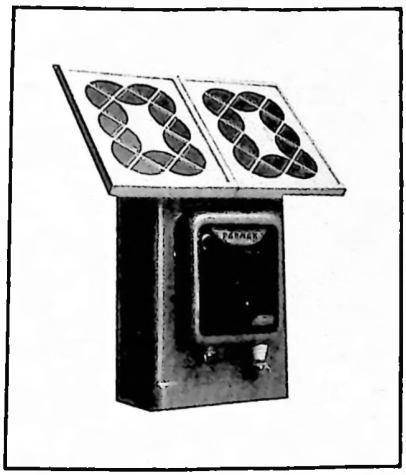


Fig. 7-3. Solar power can send an electrical charge through up to 25 miles of fence—for use on a farm, for example—using this sun-powered electric fence charger. The 12-volt apparatus can work for up to 21 days without direct sunlight and never needs battery replacement or other repairs.

provide hundreds of different circuits. The solar cells in the kit are packaged in modules so that they can be handled without the fear of damaging the cells. Electrical connections are already made to the cells so the problem of carefully soldering leads is avoided. This is particularly helpful in classroom situations where unprotected cells might be damaged by inexperienced students.

The kit contains a small motor and a buzzer that can be operated by the solar cells. An instruction book is provided that gives the characteristics of the components and circuits

Fig. 7-4. Solar energy kit includes mini-panel, motor, and rotor.

that can be built by the experimenter. The contents of the kit are as follows:

- 4 solar cell modules
- 1 electric motor module
- 1 buzzer module
- 1 rheostat module (10 to 100 ohms)
- 4 250-millimeter leads
- 500-millimeter leads
- 1-millimeter lead
- 1 ammeter module (0 to 1 ampere)
- 1 voltmeter module (0 to 5 volts)
- 1 rheostat module (0.5 to 5.0 ohms)

DIRECT SOLAR-ELECTRIC POWER

There are many projects that the experimenter can build that will only operate when there is light available. In these experiments the solar cells are connected directly to the device to be operated without any storage batteries.

When using the solar cell without any storage battery, its characteristics as a source must be taken into consideration. The familiar sources of power for electronic circuits such as batteries and power supplies have a very low internal impedance. This is the same as saying that their terminal voltages tend to stay relatively constant while the current varies with the load. A solar cell is somewhat different. As we explained in an earlier chapter, when the light is constant, the solar cell will look much more like a constant current source over a wide range of load variation.

Thus to apply a solar cell in powering something like a small transistor radio, we will need to do something to make it behave more like a constant voltage source. Fortunately, this is relatively easy. About all we have to do is to put a rather large capacitor across the output of the solar cell. The arrangement is shown in Fig. 7-6. The size of the capacitor is not critical, but in general, the larger the better. Because of the fact that solar cells have a low output voltage, the capacitors are relatively inexpensive.

Fig. 7-5. Photovoltaic demonstration kit.

Figure 7-7 shows the diagram of a solar electric generator that can be used to power a wide variety of electronic circuits including radio receivers, transmitters, and small instruments. The output voltage of the array is 5.85 volts and the available current depends on the size of the individual cells and the amount of light available. This particular voltage was chosen because most small transistor circuits

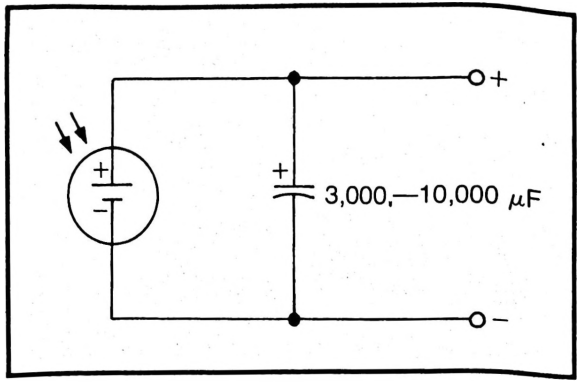


Fig. 7-6. Using a capacitor to regulate the voltage from a solar cell.

will work well at 6 volts, but there is nothing magic about it. Any series combination of cells can be used to provide the desired terminal voltage for any particular application.

BATTERY CHARGING

The big limitation of the direct solar-electric generator described in the above paragraphs is that it will only furnish power when it is illuminated. Although this is acceptable for many applications, in the general case we want equipment to operate at any hour whether or not daylight is available. This is easily accomplished by including a storage battery of some type in the generator. The solar cell or cells can then be used to charge the battery when daylight is available.

Figure 7-8 shows a solar-electric battery charger. The number of cells used in the solar array depends on the voltage and current required. The diode is included to assure that current will only flow in one direction and the battery will not discharge through the solar cells when there is no light. The resistor is provided to limit the charging current. In many small battery chargers, the resistor will not be required at all. Some sealed lead-acid batteries are designed to float across a charger at all times. In other cases, where not much current is drawn from the battery during the night, there may be a

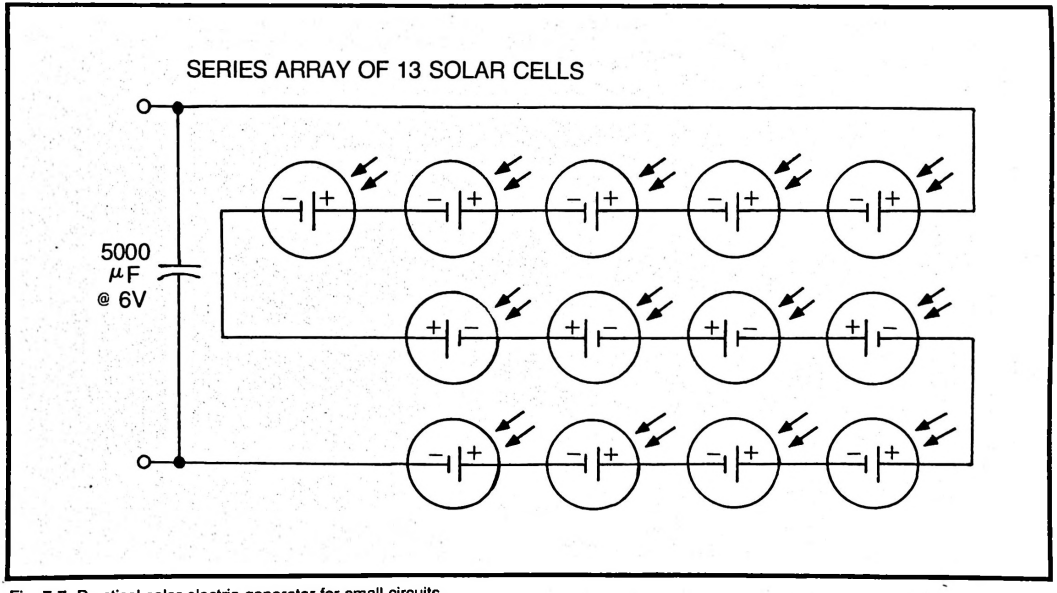


Fig. 7-7. Practical solar-electric generator for small circuits.

danger of the battery overcharging during the day.

The voltage output from the solar battery charger should be selected to provide enough charging current to recharge the battery during daylight hours. The techniques explained in Chapter 5 can be applied here. Usually a nominal voltage output of 14 volts works well for charging 12-volt batteries and 28 volts is satisfactory for charging 24-volt batteries.

When a battery charger is designed to recharge the batteries in an existing piece of equipment, the designer has little choice as to the voltage and current rating of the charger. These will be determined by the voltage and current ratings and the duty cycle of the device. However, if a piece of equipment is being designed specifically to be powered by solar electricity, the designer can do many things to simplify the power supply.

One thing that can be done when designing a device to operate from a solar-electric supply is to design the circuit to minimize power consumption. If readouts are used, the liquid crystal has a distinct advantage over light-emitting diodes as far as power consumption is concerned. Similarly, in digital circuits, CMOS technology consumes much less power than TTL chips. In analog circuits the "micropower" operational amplifiers have an advantage.

INCREASING VOLTAGE FROM SOLAR CELLS

In applying solar electricity to some small electronic projects, we run across the situation where two or three solar cells will provide enough power to operate the device in question, but will not furnish enough voltage. Rather than add more solar cells to the generator just to increase the voltage, it might be worthwhile to build a small inverter and voltage multiplier.

Figure 7-9 shows the circuit diagram of a small multivibrator that will operate on a very small supply voltage. This circuit uses germanium transistors because the base to emitter voltage across a germanium transistor is only about 0.2

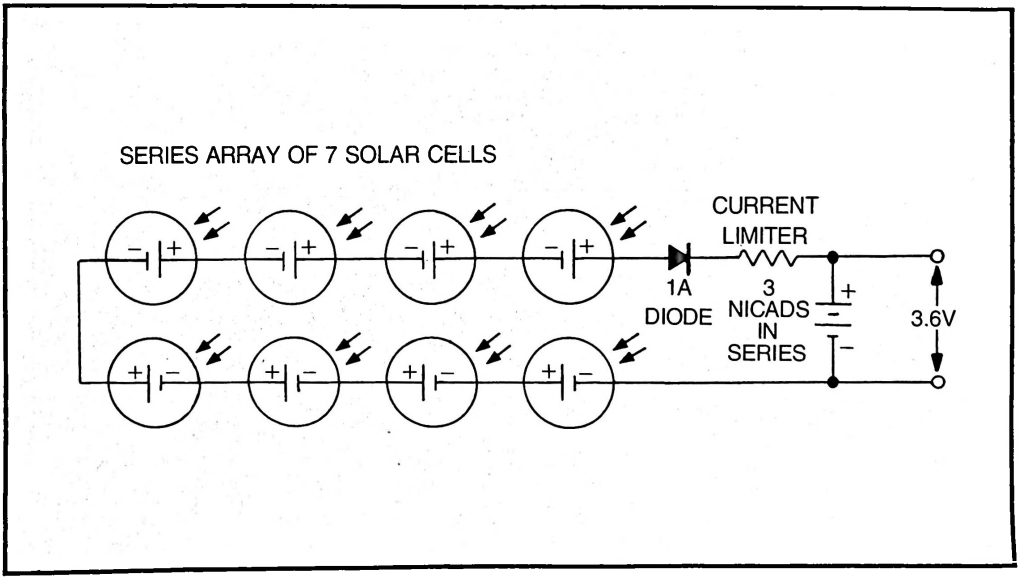
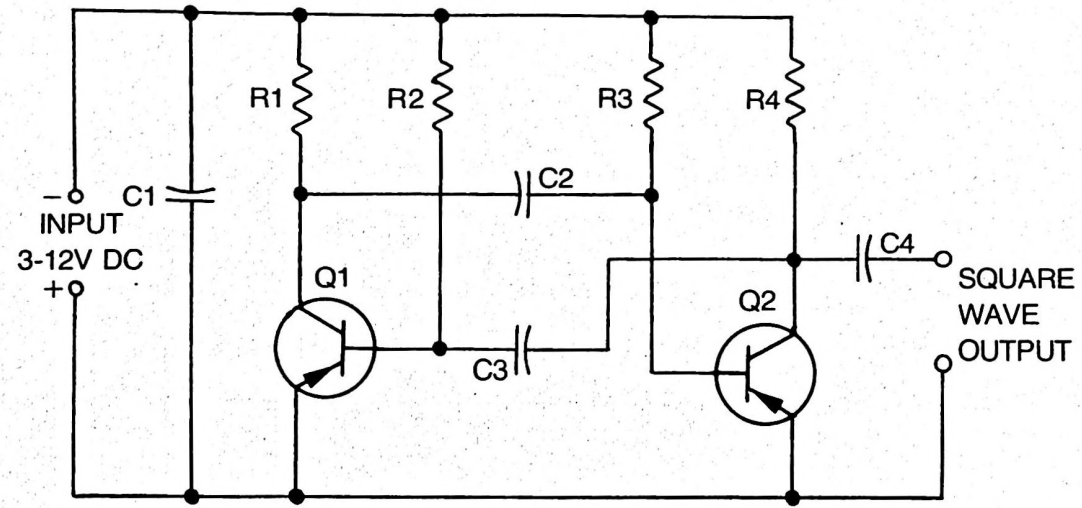


Fig. 7-8. Battery charger.



C1—3000 μF, 16V ELECTROLYTIC CAPACITOR
C2, C3—0.001 μF, 25V CERAMIC DISC CAPACITOR
C4—0.01 μF, 25V CERAMIC DISC CAPACITOR
Q1, Q2—PNP TRANSISTOR, 2N3906 OR EQUAL
R1, R4—1K, ½W RESISTOR
R2, R3—100K, ½W RESISTOR

Fig. 7-9. Multivibrator inverts DC voltage from solar cell.

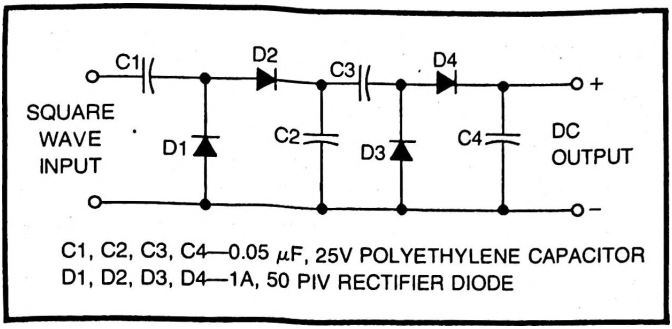


Fig. 7-10. Voltage multiplier.

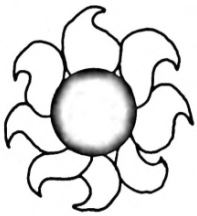
volt, whereas the base to emitter voltage of a silicon transistor is about 0.7 volt.

The multivibrator is actually a square wave oscillator. It's output is a square wave alternating current waveform having a frequency of about 1000 hertz. Now that we have an alternating voltage, we can increase it by using a voltage multiplier.

Figure 7-10 shows the circuit of a voltage multiplier. This particular circuit will triple the voltage from the multivibrator, but by adding sections we can get an increasing amount of voltage multiplication. Remember, that although the circuit will increase voltage, it cannot increase power. Therefore, every time that we increase the voltage, the circuit will furnish less current—$P = IE$.

The multivibrator shown in Fig. 7-10 will operate at a low voltage. It will always start at 3 volts and with a little careful trimming of the values of the various components, it can be made to operate at applied voltages as low as 1 volt.

Chapter 8
Accessories



Installation of a solar-electric generator can be simplified considerably by the use of accessories that save the designer time and effort. These accessories include charge controllers, an ampere-hour meter, a tracking pedestal, and various items of mounting hardware.

CHARGE CONTROLLER

Whenever the ampere-hour output of a solar generator is more than about five percent of the ampere-hour rating of the storage batteries that are used with it, it is recommended that some form of charge control be employed. Otherwise, the batteries may be overcharged. At the best this may mean that the electrolyte will evaporate requiring refilling, and at worst it may damage the batteries.

The Solarex Powermizer® charge controller was developed specifically for use in solar electric systems (Fig. 8-1). It is fully compatible with all types of solar panels, as well as with various types of storage batteries including lead-acid, nickel-cadmium, and gelled electrolyte types. The charge controller has solid-state circuitry so it will tend to have a life as long as that of the solar cells.

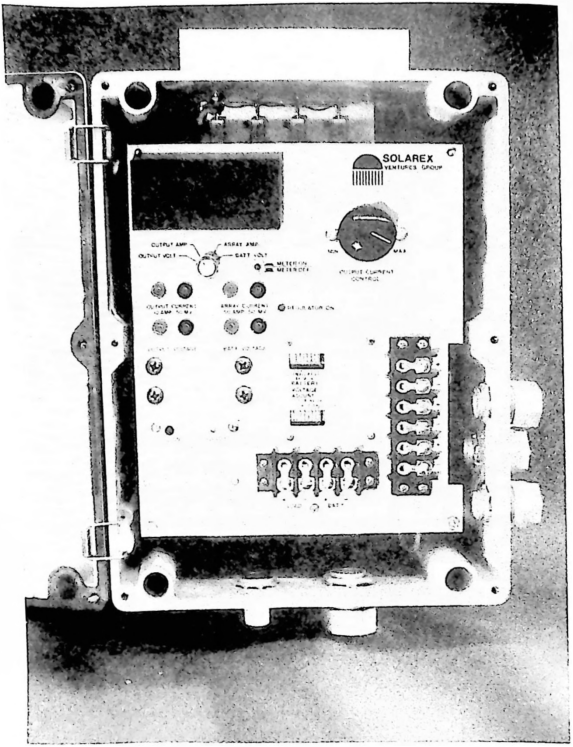


Fig. 8-1. Powermizer charge controller. Developed specifically for solar electric generators, the Powermizer prevents overcharging of storage batteries.

MEASUREMENT EQUIPMENT

Figure 8-2 shows ampere-hour meter and watt-hour meters. The ampere-hour meter will indicate the actual ampere-hour output of the panel. This arrangement will give the best possible indication of the amount of solar energy available at any particular location. By leaving the calibrated solar panel in a given location for an extended period of time, we will get a factual measure of the amount of energy. The

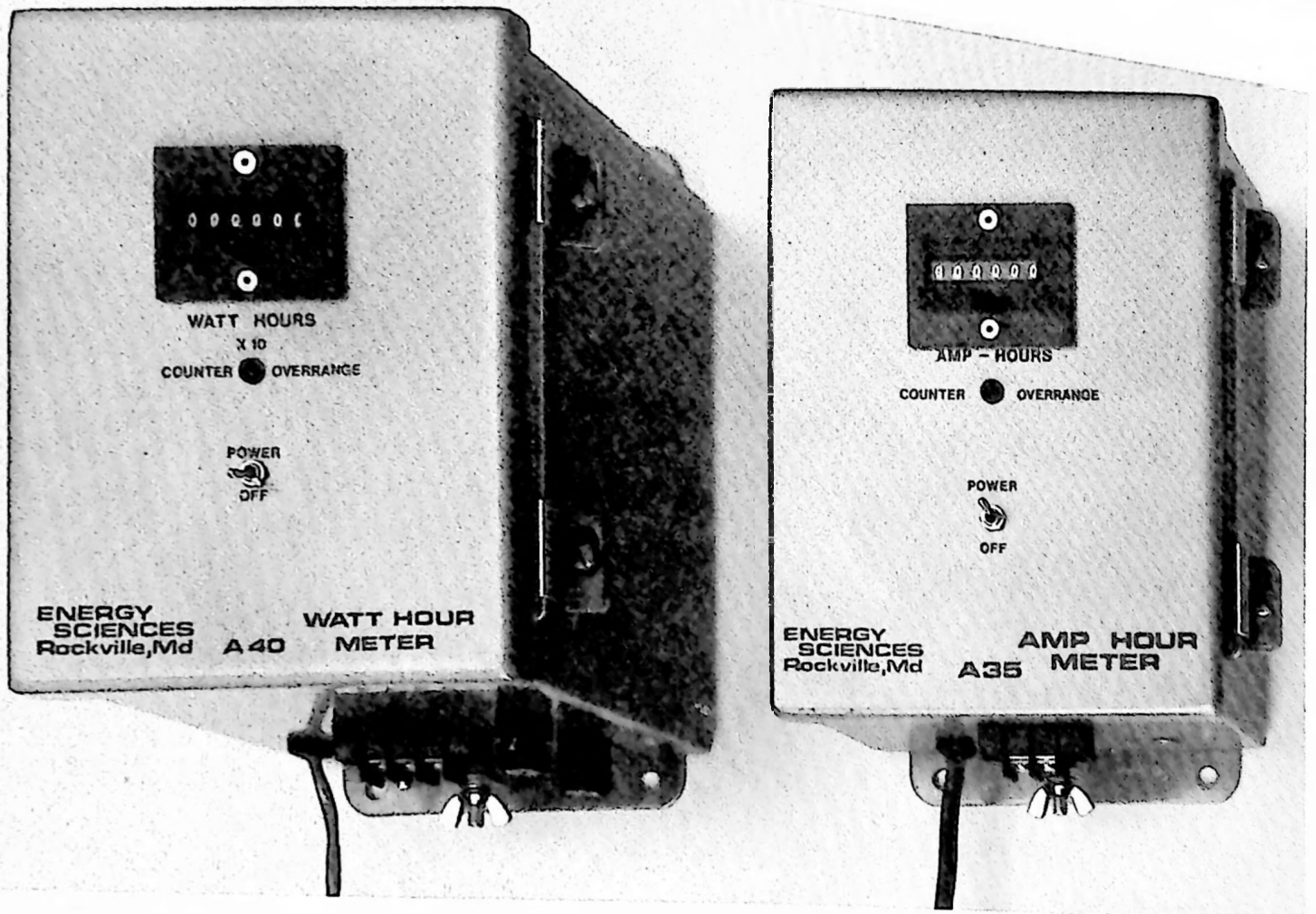


Fig. 8-2. Ampere-hour meter and watt-hour meter.

arrangement has the advantage that it requires no attention at all. Once installed, it will continuously monitor the ampere-hours produced by the calibrated panel.

TRACKERS

As we have mentioned earlier, the best orientation for a solar array in most parts of the United States is due south. Of course, this means that the array is not pointed directly at the sun all day long, but is pointed in the correct direction during the hours of maximum daylight. In instances where concentrator cells are used to get the maximum possible amount of energy from the sun in a limited space, it is helpful to keep the array of solar cells pointed directly at the sun at all times.

A tracking pedestal contains motors that will keep the array pointed at the sun at all times. A small sensor mounted on the array provides electrical signals that tell the control system which way to turn the array to get maximum sunlight.

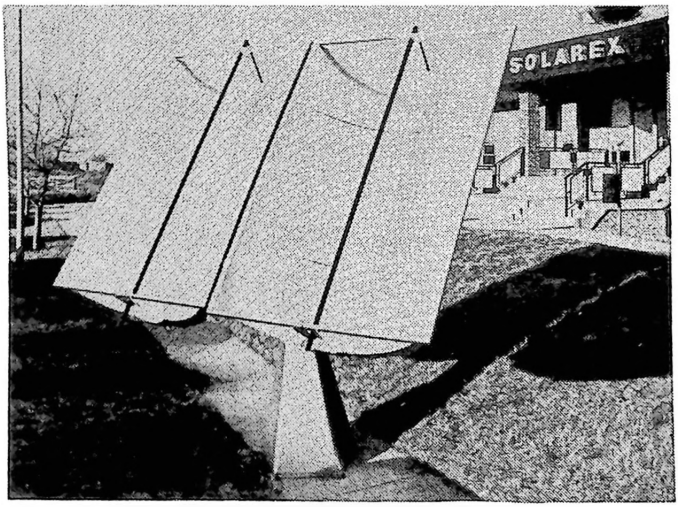


Fig. 8-3. Dual-axis tracker. This tracking device is weatherproof and mechanically simple, yet provides enough output and accurate two-axis tracking capability for solar-electric and thermal systems.

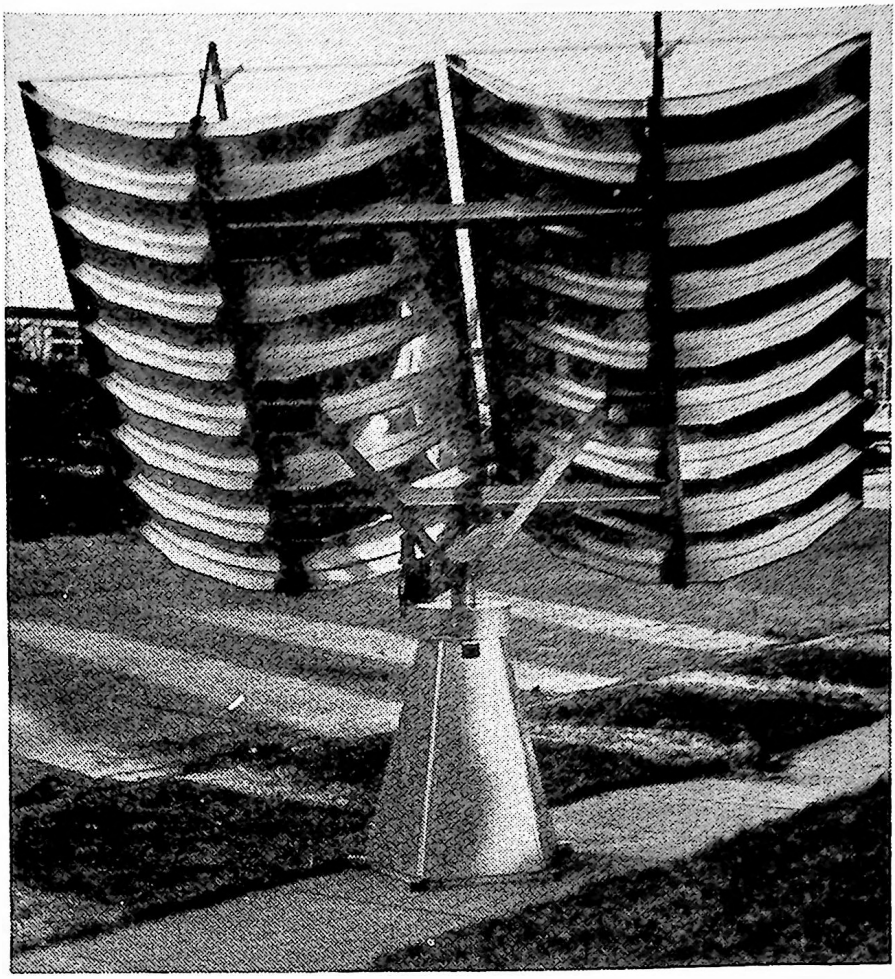
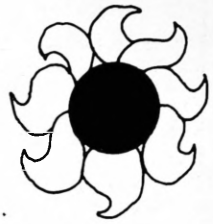


Fig. 8-4. A power module mounted on a tracker. The multicell sun sensor continually monitors the tracker's alignment with the sun. It uses solid-state circuitry to provide a voltage differential proportional to any tracking error.

Chapter 9

Nonpower Photovoltaic Cell Applications



So far in this book we have looked at the silicon photovoltaic cell as a source of electrical power. Indeed, this is probably the most significant application of the photovoltaic effect. We must not forget, however, that the solar cell is a light sensitive device and therefore has many applications other than converting light into useful quantities of electrical energy. In many circuits, a solar cell can be used both to sense the level of light and to provide operating power for the circuit. In this chapter we will consider a few of the nonpower applications of solar cells.

LIGHT METER

Inasmuch as the solar cell responds to the light level, we can use it with a meter to measure or sense the level of light. In our study of the properties of the silicon solar cell we found that, except for very low light levels, the current output of the cell is very nearly proportional to the power density of the incident light. This means that to measure the output of the cell, we will do best if we measure the short-circuit current output of the cell. We can best do this with a microammeter or milliammeter. Fortunately, most multimeters have milliam-

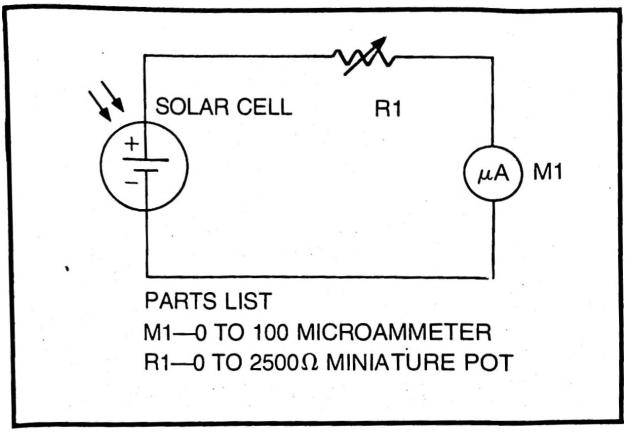


Fig. 9-1. Use of a solar cell in a light meter.

pere scales and many have microampere scales. We do not want to use a voltmeter, because with a constant load, the voltage output of a cell doesn't change very much with changing light levels.

Figure 9-1 shows the circuit of a simple light meter. Here a multimeter is used as an indicating instrument. The various current scales of the multimeter can be used to give different ranges of light level measurement.

Calibration of the light meter poses a few problems. Remember that although the resistance of an ammeter is very low, it is still not zero so we won't actually get the short-circuit current of the cell. The microampere ranges of some multimeters actually have a rather high resistance. The best way to calibrate a light meter is to use the services of a photometric laboratory. Some camera shops that repair exposure meters have equipment that can be used for calibration.

When nothing better is available, some rough calibration can be made by placing the solar cell right beside a photographic exposure meter and subjecting the pair to varying light levels. The light meter can then be at least roughly calibrated according to the indication of the exposure meter. Lacking any

means at all of calibrating the light meter, you can always use it to give a relative indication of the available light.

A light meter can be used to demonstrate many interesting properties of light. For example, the meter can be placed in front of a light source and various materials inserted in the path of the light. It is interesting that objects that appear to be transparent, such as pieces of glass or plastic, will actually reduce the amount of light reaching the meter. Blowing smoke between the light source and the light meter will show how photovoltaic cells can be used in a smoke detector.

LIGHT-OPERATED RELAYS

Another application of the solar cell is to operate a relay. If a sensitive relay is available, it may be operated directly by the output of the solar cell without any other power supply. A typical circuit is shown in Fig. 9-2. Most relays that are readily available will not operate on the output of a single solar cell. The reason is the resistance of the coil of the relay is usually too high. The current from the solar cell is great enough to operate the relay, but the voltage isn't high enough. There are

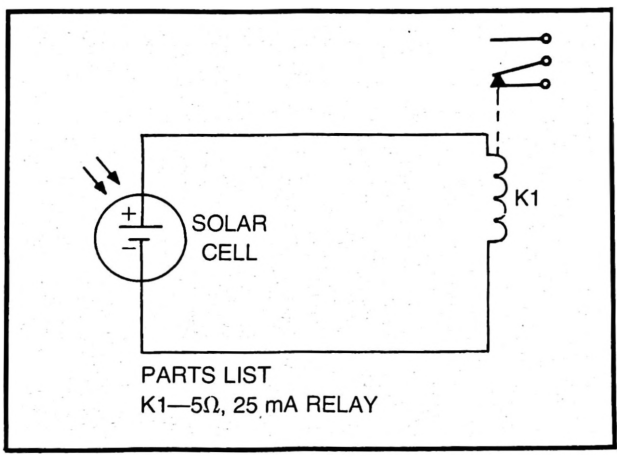


Fig. 9-2. Light-sensitive relay.

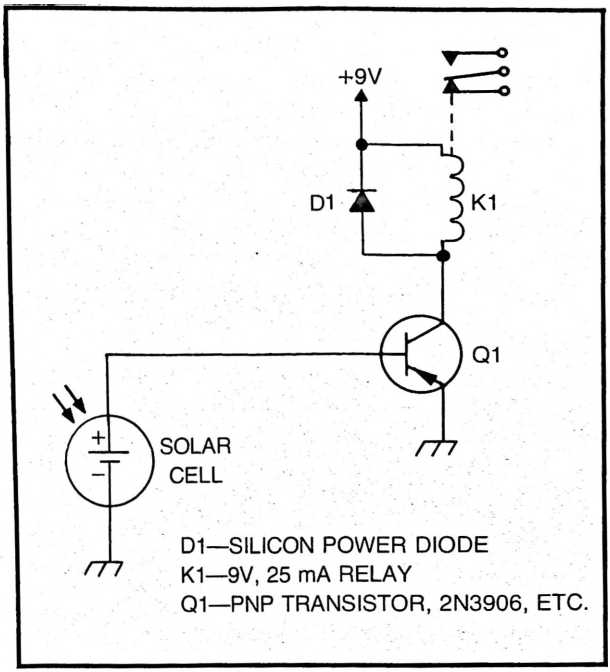


Fig. 9-3. Light-operated relay with amplification.

two approaches to avoiding the cost of a low resistance relay. One is to simply use a few more solar cells in series to increase the voltage output. Another is for the experimenter to make his own relay.

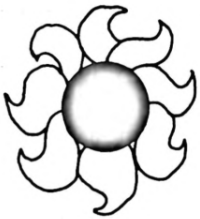
Building a relay isn't difficult because of the availability of magnetic reed relays. These relays are available with coil forms so that the experimenter can wind his own coils. Furthermore a small permanent magnet may be placed near the relay to provide almost, but not quite, enough magnetic force to operate the relay. All the coil of the relay will then have to do is to provide enough additional force to operate the relay.

If an extra power supply isn't objectional, a larger less sensitive relay may be used with a transistor amplifier. Figure

9-3 shows a typical circuit. Note that if a germanium transistor is used, the output of a single solar cell will operate the circuit. This is because the base-emitter voltage of the germanium transistor is much less than that of a silicon transistor.

The applications of a light-operated relay are many. Note that we have used a single-pole, double-throw relay in the circuit of Fig. 9-3. Thus we can either turn something on or turn it off when the light level increases. A typical application is a circuit that turns off outside lights during daylight hours. Another application might be where a flashlight is used as a light source to control something or other.

Chapter 10
Recent Advances and Current Research



Solar electric technology has come a long way since the first practical applications of the photovoltaic effect in the U.S. space program in the 1950's. Today solar electricity is accepted as an alternate source of power in a wide variety of terrestrial settings and as "first choice" in many situations in which conventionally generated electricity is either entirely unavailable or too expensive.

Research is continuing and moving rapidly. Current research into photovoltaics has focused primarily on two areas: on improving the efficiency and performance of solar cells and systems and on reducing the cost of sun power.

These two considerations are tightly interrelated: The amount of power produced by a solar cell becomes a better buy the lower the cost of that cell goes. That was why the invention of the high-efficiency solar cell in 1973 was such a milestone. For the first time it brought the cost of solar electricity down dramatically—from the neighborhood of $500 per peak watt to about $20 per peak watt by 1977.

In the 1980's, a similar technological breakthrough is promising to reduce this cost still further. Until recently, solar cells had been made exclusively from high-purity

single-crystal silicon, an expensive material that is not always easily available and demands a lot of energy in its own manufacturing process. That's ironic, because silicon is the second most abundant element on earth.

Now, Solarex Corporation's affiliate, Semix, Incorporated, has developed a way to use low-purity raw silicon in the manufacture of solar cells that perform as well as, or better than, the high-purity single-crystal cells that preceded them.

This development cuts the cost of material drastically and eliminates worry about interruptions in the steady supply of silicon needed to produce solar cells. It also makes it possible to manufacture solar cells and panels more quickly and in larger quantities than has been the case before. This increased productivity makes large-scale applications more feasible.

In addition, the variety of round, crescent and other shapes used in solar cells in the past have been replaced by a uniform square-cell configuration 10 cm on a side. Using square cells makes it possible to pack cells onto a panel much more densely, leaving much less unproductive space between cells than ever before.

The combination of advances—cheaper materials, faster construction in larger quantities, and higher per-panel efficiency—means the cost of solar electricity will continue to decline dramatically. For example, while the cost per peak watt of solar power was around $500 in the early days and declined to about $20 by 1977, today it is about $10. It is estimated that by the time photovoltaic demand reached the 100 megawatt level, costs will have dropped below $4 per watt. The period of time required for a solar installation to pay for itself in energy savings has dwindled from more than 6 years in 1977 to about 3.5 years today and will decline to less than a year by the time 100-MW demand—and the $4 per peak watt cost level—is achieved.

The first commercial application of these new technologies is in the Solarex SX Series photovoltaic panels.

These highly efficient 17.5-inch by 42-inch panels produce between 32 and 40 watts of peak power at 17 to 17.5 volts and are more economical to buy and install than any previous panel.

SX Series panels—3,120 of them—provide an average of 800 kilowatt-hours per day or energy to power an extraordinary new facility Solarex has constructed to manufacture solar cells. Located outside the city of Frederick, Maryland, this facility is the world's first "solar breeder." It opened in October, 1982.

The solar breeder isn't even connected to a utility grid and uses no oil or gas for heating. In short, it is entirely independent. Inside, a state-of-the-art semiautomatic manufacturing line will produce high-efficiency 10-cm-square solar cells from low-cost semicrystalline silicon. On the roof, 28,000 square feet of solar panels provide all the building's power needs. Coupled with a battery system that can store up to 2.5 megawatts, this facility could operate at full productivity for four consecutive days in the total absence of sunlight. Associated passive-solar thermal-energy systems

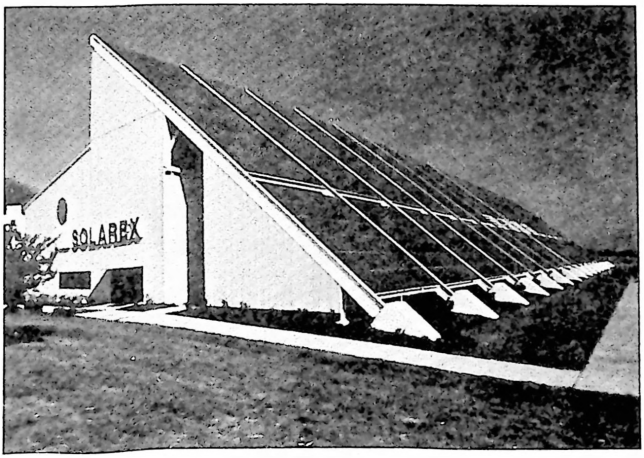


Fig. 10-1. The new Solarex Corporation "solar breeder" in Frederick, Maryland, isn't even connected to a utility grid—it gets all the power it needs from the solar panel array on the roof. Now solar power creates new solar cells!

provide the heating requirements of the facility. Computers control and regulate the entire operation.

Thus, for the first time, man is using solar-generated electricity to manufacture, or "breed," additional solar-electric cells.

The photographs on these pages show several stages in the evolution of the new solar breeder—from completion of the supporting framework, through attachment of the SX panels leading to completion of the building and its dedication by the Governor of Maryland, Harold Hughes, on October 5, 1982.

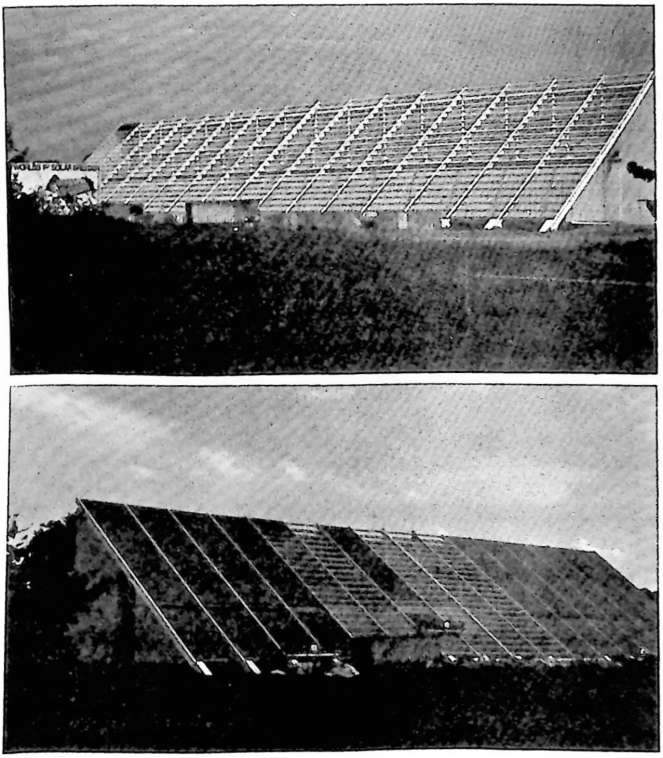


Fig. 10-2. These photographs chronicle the construction of the Solarex solar breeder from basic framework through installation of the 3,120 Solarex SX-panels, to dedication of the facility by the Governor of Maryland.

NEW CELLS FOR THE SPACE PROGRAM

The space program gave the solar-electric industry its birth, and in the 1980's researchers have been deeply involved in developing new, more efficient, higher-output and lower-cost solar cells expressly for use in outer space.

Outer space is a radically different environment for a photovoltaic system. The intensity of light reaching the cell material is quite a bit greater than on the surface of the earth. However, much of this added intensity is at the ultraviolet end if the spectrum—light energy that is not usable for the solar cell and much of which is normally filtered out by the Earth's atmosphere.

The result is a paradox: Although the output of the solar cell goes up, its "efficiency," defined as the ratio of light energy received to electrical energy produced, goes down. Output and efficiency, however, are only two of the many factors that must be weighed in designing a photovoltaic system for use on spacecraft.

The space environment is filled with radiation in many forms that are either less potent or nonexistent on earth. For example, belts of electromagnetic energy surround the Earth and other planets and similar bodies. Anyone who has ever worked with electronic devices knows that exposure to magnetic fields can effect the device's performance dramatically. In addition, large numbers of highly charged subatomic particles sweep through space unpredictably as a result of solar flares and the like.

These charged particles can damage the silicon crystal. Remember, or review, the description of how a semiconductor works, set forth in Chapter 2. Remember that the silicon material on one side of the semiconductor junction contains free electrons—that is, more electrons than there are spaces in the atomic structure of the silicon. On the other side of the junction there are "holes"—spaces where electrons should be but aren't. Light striking the silicon provides the energy that enables the free electrons in one area to

move across the junction and fill in the holes in the other area.

Now imagine what happens when that silicon material is struck by a very powerful and unexpected jolt of energy. Often, the result is to create "traps" in the N-type silicon that can trap many electrons before they ever have a chance to reach the junction point. This *radiation degradation* can have a very marked adverse effect on a solar cell's performance. Because the cell in outer space will be exposed to this and many other types of radiation over many years, resistance to degradation is vitally important.

A variety of approaches are being tried to reduce the vulnerability of solar cells to radiation degradation. One key is to minimize the distance a free electron must travel to reach the semiconductor junction. An example of this approach is in the new Vertical Junction cells being developed experimentally by Solarex.

A Vertical Junction cell is shown in Fig. 10-3. The N-type silicon, the material that contains extra electrons, is distributed in a pattern of "teeth" with space between. These teeth are overlaid with a film of P-type silicon. In this arrangement, instead of having to travel all the way to the surface of the cell, a free electron can cross the junction and fill a hole by moving to the nearest side surface. In effect, no matter where in the N-type silicon a free electron is located, it will be closer to the junction than it would generally be in the conventional flat cell.

The productive surface area of the cell is also dramatically increased in a Vertical Junction cell.

There are a number of aspects of Vertical Junction cells that require additional research—for instance, the optimum depth of the tooth pattern. It is unlikely that Vertical Junction cells will have terrestrial applications any time soon, but for outer space they may offer a solution to the problem of vulnerability to radiation degradation, as well as a more efficient, higher-output cell type.

Materials other than silicon are also being investigated.

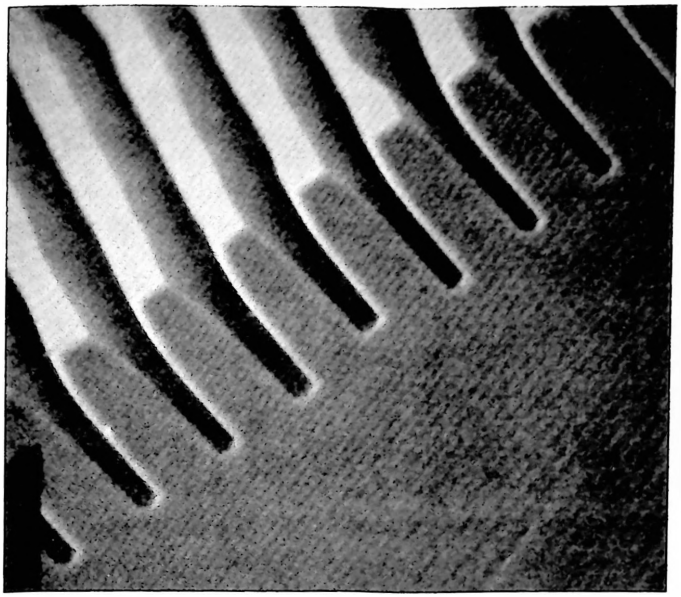


Fig. 10-3. The Vertical Junction cell is one type of solar cell being studied for suitability for outer space uses. Researchers believe its unique design will make it less vulnerable to electromagnetic radiation in space.

Silicon has been ideal for solar cells because of its low cost and easy availability, but in outer space cost becomes a less critical consideration. First, such values as efficiency, dependability, and radiation resistance may outweigh cost in the selection of a material. Second, a solar-powered apparatus, even a costly one, is likely to make up a relatively small share of the total cost of a spacecraft.

Gallium arsenide has been of interest to many researchers, including Solarex, as a possible substitute for silicon in space cells. It is an efficient solar converter and offers good temperature coefficients for voltage and power of warm spacecraft. However, it is, at present, about 100 times more expensive to build a solar cell with gallium arsenide than with silicon.

Amorphous silicon is another possibility. This is silicon applied as a very thin film, much thinner than any solar cell in

use today. Often, it is sprayed onto a substrate. Its advantage is cheapness: it's quite a bit less expensive even than the new, semicrystalline silicon used in terrestial cells. So far, however, its power output has been such that it hasn't shown much promise of being cost-effective even at a very low cost.

The demands on the solar energy industry will increase as space programs expand and multiply. Not long ago the only customer for space cells was the United States government. Now, the government, various military agencies, private communications corporations, weather services, quasi-governmental bodies as the European Space Agency, and a large number of other "buyers" are heightening the demand for all kinds of aerospace materials and equipment. Their demand for better performance at a better price will inevitably result in superior new products that could have an influence on terrestrial applications as well.

The next 10 years may be the most exciting and productive years yet for the solar power industry.

CATHODIC PROTECTION

The usefulness of solar electricity in cathodic protection of metal structures was described in Chapter 6. Today, applications of photovoltaics are becoming more widespread than ever before as research improves the reliability of photovoltaic cathodic protection systems and reduces the costs associated with it.

The chief applications area for solar cathodic protection today is in oil and gas wells, with increasing attention to pipeline settings. In the United States, in spite of the availability of utility power in most areas, we have hundreds of locations where the power line extension is more expensive than the cost of a complete system of solar panels; therefore, it has made commonplace the use of solar cathodic protection units.

In developing nations where utility power is less com-

monplace, and where new pipelines are being laid for the supply of oil or gas for large cities or from their large oil-producing areas, the use of photovoltaic energy is a natural and obviously cost-economical solution.

New efforts and developments are being introduced to standardize design and structural elements, as well as improve regulation and storage systems, enabling today's photovoltaic cathodic protection systems to function at virtual 100 percent reliability levels with little or no attention, that is, a steady effective electrical current generated 100 percent of the time.

In cathodic protection, progress is steady. Although there have been no big, attention-getting "breakthroughs," today's cathodic protection systems are better than those available just five years ago. Five years from now the systems available to designers and engineers will be better still.

NAVIGATIONAL AIDS

At first glance, marking navigational hazards like shoals and underwater rock formations (as well as remote airports and tall towers) would seem to be an ideal application of photovoltaic technology.

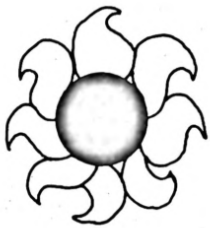
That is true, but there are also some major problems associated with these applications. It's a field in which aggressive research and development are taking place.

For example, maritime navigational markers must function in an extraordinarily hostile climate. Stresses on a photovoltaic system are additive to a great degree. For example, a solar-powered system can function quite well in conditions of high humidity—*or* high wind, or high salt content in the air—but when all of these conditions exist at once, the result is a very severe test of all system components.

Both the United States and Canadian Coast Guards have launched pilot programs to test photovoltaic systems for these demanding uses. Use of photovoltaic systems to power

buoys, lighthouses, and other warning signals are already common and becoming more so. As development continues, new, better systems are being developed to provide more reliable and less costly solutions to these difficult applications problems.

Chapter 11
Solar Electricity in the Home



One consequence of rising energy prices in the past decade has been that people are most sensitive to energy costs and more interested in ways of reducing their dependence on utility-provided power. At the same time, advances in energy technology have made it practical for many people to act on that interest, in effect, to declare their personal energy independence today.

Solar electricity is an exciting example. In some cases comparing the cost of a complete photovoltaic power generation and storage system for a home with the cost of connecting the home to the local utility grid will show that photovoltaic power is economically competitive right now. In even more instances, photovoltaics become competitive—even a bargain—when long-term costs are weighed, including inevitable further utility rate increases.

If you are considering a solar-powered system for your own home, there are a number of factors you need to assess. You'll want to examine all of these questions in detail. There are a great many books on the market as well as a growing number of consultants and contractors who specialize in alternative energy installations that can help you. We won't

try to match that exhaustive treatment here; instead, we'll outline some of the key decisions you need to make and some of the factors you need to consider in making them. Specifically, we'll address:

- Is solar electricity for you?
- What components do you need, and what jobs do they do?
- How should you estimate your system needs?
- Should you strive for complete independence or build a system that interacts with the local utility company?

THE BASIC SOLAR DECISION

The basic question you must face first is simple: Can solar electricity pay off for you in your particular circumstances? To make this choice, you have to put aside intangible factors as much as possible. Sure, if you're an avid do-it-yourselfer, the enjoyment of working on the system is an extra "payoff," but recognize that for the emotional factor it is. Try to get as close as possible to a real dollars-and-cents objective evaluation.

The first thing to examine is your site. If your homesite is one-half mile or more from the nearest utility power, you're facing some major costs in obtaining that power. You'll have to pay for a connection to the grid, for labor and materials to run a line to your house, for on-site installation and related equipment, and maybe for quite a bit more. Your local utility company can give you a specific quote for your site. Bear in mind that this one-time cost, which can be substantial, only buys you the right to use utility-generated power, which you then have to pay for every month.

As a general rule, where utility power is already available or easy to obtain, solar electricity is less competitive. It can still, however, be attractive over the long haul.

With your utility estimate in hand, take another look at your site. Does it receive enough sunlight to make solar electricity feasible? If your house and the site where you propose to mount your solar arrays are shaded by trees, weigh the passive cooling effect of the trees (together with the esthetic satisfaction they provide) against the gain from

trimming them back, moving them, or cutting them down. Site considerations can be complicated, but in general your proposed site should have full sunlight striking it between 9 AM and 3 PM each day. You can make actual measurements of sunlight reaching your site, or you can refer to a variety of national and regional *insolation* maps available commercially. These provide average peak sunlight hours per day for the specific area in which you are interested and may be more accurate than your own estimates.

You can refer back to Chapter 5 for additional information on how to use and adjust this insolation data to make it really relevant to your specific needs.

Is it possible, on your existing house or site, to orient your solar-panel arrays for maximum efficiency? Clearly, for any site in the United States, your array must face south, and as close to true south as possible. True south can differ from the south reading shown on a compass by quite a bit. A local surveyor can tell you the appropriate correction factor for your area. The position of the sun in the sky will vary with the seasons, and if you are building a fixed array, you should cnsider whether your needs will be greater in the cooling o heating season.

You can also adjust the orientation of your array several times a year for maximum solar exposure. A "tracking" array, a solar panel array that follows the sun from east to west across the sky, can increase your electrical production from 20 to 40 percent.

From all of these considerations, you will arrive at a decision on whether you can realistically expect to generate enough electricity from sunlight *at your site* to make the initial investment worthwhile, or whether it will still be cheaper for you to rely on the utility company.

You also need to make a comparison of the real advantages and disadvantages of a solar system.

The advantages are clear: Once in place, the system produces no monthly electric bill, uses no fuel, and needs

very little maintenance. You'll be free of utility rate hikes, power failures and outages. You can expand your system as needed in the future. And solar power doesn't pollute at the point of use.

On the other hand, installation costs can be very substantial and all up-front. There's more to consider, however, because the federal government, and many states, offer tax credits, deductions and other incentives to people installing solar systems. These can reduce the initial cash cost by as much as 40 percent or more. Check with your state tax office for details.

You won't be getting power from your array at night or on cloudy days, so some storage facility is needed. That means storage batteries, which add to cost and require periodic service. You'll either have to convert your home to DC current or use a power inverter to produce AC. You may need a backup generator to keep your batteries fully charged, and you power output per dollar invested is going to be fairly low.

The values you assign to these variables will change depending on where you are and how you live. What's important, though, is to be fully aware of what these factors are and how to measure them.

WHAT COMPONENTS DO YOU NEED?

The striking panel array mounted on the roof may be the most visible aspect of a household photovoltaic system, but it won't amount to much without a fairly extensive list of support and backup apparatus. Every system needs three elements: a means of collecting electricity from sunlight, a means of storing it for use when the sun isn't shining, and a means of conveying this power to the load it has to operate.

Chapters 4 and 5 provided a fairly complete introduction to the types and functions of solar panels, batteries, and related devices. We won't repeat that introduction, except to note again that the basic decisions hinge on your own individual circumstances. For example, are you designing a system for a remote home, a vacation home or some other

site where 12-volt DC current could be used? Wiring a 12-volt DC circuit is fairly easy, and DC appliances are readily available. If you're starting from scratch, DC may be a good option.

If you're retro-fitting an existing home, on the other hand, you probably don't want to buy all new appliances and fixtures, so some means of converting the 12-volt DC current from the solar panels into 120-volt AC current for your loads is needed.

You can also set up your household system to use both 12-volt DC loads and 120-volt AC by using inverters where needed and letting the direct current from the panels power whatever devices can be obtained in, or easily converted to, a 12-volt basis.

Weather conditions at your site will also determine exactly how much storage capacity you need. If you're building a system completely separate from utility power, you either need to ensure adequate power from your system or provide a back-up facility such as a generator.

Once both the panels and the batteries are in place, you need some means of deciding whether you should run your system off the panel current or off battery power, and you need some means of controlling the charge delivered to the batteries. One means is a simple voltage regulator, which will route excess, unneeded power to the batteries whenever possible. A more sophisticated tool is a full system controller. This device, which can be computer-controlled, will monitor the performance of every element of your power system, distribute power accordingly and call attention to failings.

Your battery needs are determined by your power usage. We gave some attention to this subject in Chapter 5, and we'll talk a little more about it later.

SIZING YOUR SYSTEM

Photovoltaics can be a practical household energy source *if* you live energy-consciously. One thing a photovoltaic system will definitely do is give you a better understanding of the fact that electric power is neither free nor unlimited, and this, in turn will make you more mindful of

how you and your family use electricity and ways in which you can conserve it.

How much do you need in the way of a photovoltaic system? This is a difficult question, since it can be approached two ways. First, what would it take to support whatever lifestyle you now have? Second, what would you need to provide power for all the necessities of your household if you and your family cut back or eliminated wasteful uses of power?

Conduct an energy-use survey of your household. Don't just estimate or assume values, make a real measurement over a period of time. What lights do you burn, what kind of lights are they, and how long do you use them? Could you do without them? How much television do you watch, and what is the power consumption of your set? Do you cook with electricity? If so, how often, for how long, and at what rate of consumption? What forms of recreation do you have that use electricity, and how do you pursue them?

This survey exercise will both tell you how you live now and give you some idea of what areas may be ripe for conservation.

Take into account the season during which you conduct the survey. If you use more power in winter than in summer, allow for that fact, even if you're actually measuring your use in summertime. It will be helpful, too, if you convert watt-hours to ampere-hours to simplify sizing of the photovoltaic panel array. Chapter 5 also provides some useful formulae both for this conversion and for the conversion of the ampere-hour figure into necessary panel output.

You'll need to divide the total daily power consumption of your household by 24 hours to arrive at the "continuous load," then multiply that figure by a particular multiplier for your geographic location (you can obtain this from insolation maps or a local contractor) to arrive at the "peak load" amps. Then, divide this need by the peak ampere rating of the solar panel you intend to use to arrive at the number of modules you'll need for your array.

Likewise, the exact number and requirements of the appliances you need to run on AC will determine the inverter types and loads required by your system.

As we noted before, there are a number of books on the market that go through the design process very intricately. They can be of great help to you if you are working up your own system specifications. As another option, a reliable contractor in your area can be a source of good advice.

INDEPENDENT OR INTERACTIVE?

Many people are intrigued by the notion of selling the power they produce to the utility company in their local area—of having the electric company pay them, instead of the other way around. This came about because federal law now requires publicly regulated utility companies to buy power from small producers.

A "grid-interactive" solar-powered system also appears to offer several other advantages: specifically, it can rely on the utility for power during low-sun or no-sun periods. Before you commit yourself to a utility-interactive system, however, consider several other factors.

First, while the utility company charges you, in effect, a retail price for the power it provides, it only pays you a wholesale price for power it buys from you. You won't, in other words, just be running your electric meter backwards. Most utility companies will install a second meter and pay you for your power at an entirely different rate from what they bill for theirs.

Furthermore, interlocking with the utility grid requires a synchronous inverter or some form of expensive power-conditioning equipment. Buying and installing that equipment costs money, and you'll need an engineer on the site while it's going in. Remember too that the synchronous inverter runs on power from the grid, so if there's a system power failure, your own solar-electric system will be useless, too. Thus, you'll still need a battery bank or another inverter to enable you to use your photovoltaic power when the grid power fails.

A good option may be to build a stand-alone system first, then re-assess whether you want to be part of the utility grid. Being part of the grid *does* have its advantages. But even if there's a brown-out or power failure, your initial stand-alone system will still be working for you.

ENERGY SCIENCES: A NEW CONSUMER'S ENERGY STORE

As with any new technology, sources of equipment for solar electricity are many and varied. Not all of them, frankly, are reliable. Often the multiplicity of devices, claims, warranties, prices, and specifications can be very confusing. To help convey its own high-quality products to the public, and to make it easier for the public to get information, advice, and supplies for photovoltaic systems, the Solarex Corporation created the Energy Sciences Company in 1981.

Energy Sciences consists of a series of retail stores that sell both Solarex products and products of other manufacturers. In addition, it offers a consumer's mail-order catalog making these products easier to obtain for people living far away from the stores. In general, Energy Sciences carries:

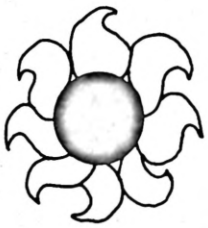
- Solarex photovoltaic cell, panels and similar devices.
- Inverters, regulators, system controllers, batteries and other equipment for use in a complete photovoltaic system.
- Appliances, tools and other devices that run on 12-volt DC current, from recreational items to hard-working household utensils such as refrigerators.
- Books on solar and alternative energy.
- Educational kits for young people to teach them about energy and other science topics.
- A wide variety of interesting sun-powered toys, tools and demonstration projects in which practical photovoltaics provide all the necessary electric power.

The technical staff at Energy Sciences can help you design your own photovoltaic system and can provide complete specifications and recommendations for selecting and using panels and other devices. They will also respond to specific enquiries by mail.

The mail-order catalog from Energy Sciences is available for $3, which is refunded on your first order of $15 or more. To purchase a catalog write to Energy Sciences, Department SGSE-2, 832 Rockville Pike, Rockville, MD 20850.

We hope you'll find more and more ways each year that practical solar electricity can make your life more independent and secure—and more fun!

Glossary of Solar-Electric Terms



absorption. When light strikes a surface, some of it penetrates into the material and doesn't come out. This is called *absorption*.

angstrom. The angstrom is a measure of the wavelength c light. One angstrom = 10 nanometers = 10^{-10} meter.

AM-air mass or atmospheric mass. This is a measure of the absorption and scattering of light by the Earth's atmosphere. AM 0 indicates no atmosphere in the path of light. This is the condition out of space where the power density of light is about 136 mW/cm². AM 1 is the condition at the surface of the Earth where the light passes through one atmosphere. Power density is about 100 mW/cm².

ampere-hour meter. An instrument that monitors current with time. The indication is the product of current in amperes and time in hours.

blocking diode. A semiconductor connected in series with a solar cell or cells and a storage battery to keep the battery from discharging through the cell when there is no output, or low output, from the solar cell.

concentration ratio. The amount that light is magnified by a focusing system. For example, if a lens or reflector system

increases the power sensitivity of sunlight from the normal 100 mW/cm^2 to 300 mW/cm^2—a magnification of three times—the concentration ratio is 1 to 3.

concentrator cell. A solar cell designed at light power densities much greater than the normal power density of sunlight at the surface of the earth. Concentrator cells can be used with focusing arrangements that increase the power density of sunlight hundreds of times.

efficiency of a solar cell. The ratio of the electrical power output of a solar cell to the solar power that it intercepts. For example, a solar cell 3 inches in diameter intercepts about 2.39 watts of solar power under full sun conditions. If the electrical output of this cell is 0.34 watt, the efficiency will be

$$\frac{0.34}{2.39} = 0.14, \text{ or } 14\%$$

full sun. The full sun condition is the amount of power density received at the surface of the Earth at noon on a clear day—about 100 mW/cm^2. Lower levels of sunlight are often expressed as 0.5 sun or 0.1 sun. A figure of 0.5 sun means that the power density of the sunlight is one-half of that of a full sun.

insolation. The amount of sunlight reaching an area. Usually expressed in milliwatts per square centimeter.

incident light. The incident light is the amount of light reaching an object.

nanometer. A unit of measurement of the wavelength of light. One nanometer = 10^{-9} meter.

photon. In the quantum theory of light, light consists of tiny bundles of energy. One of these bundles is called a *photon.*

photovoltaic cell. A photovoltaic cell is one that generates electrical energy when light falls on it. This term distinguishes it from photoconductive cell (photoresistor), which changes its electrical resistance when light falls on it.

Powermizer. A trade name of the Solarex Corporation for a battery charge controller that can be used with solar cells to prevent overcharging of a battery.

quantum yield. A technical parameter from quantum physics. For practical purposes the quantum yield of a solar cell is the spectral response of the cell, that is, the relative output at different wavelengths of light.

reflected light. When light reaches an object, some of it may be absorbed, and some may be bounced off the surface. The light which is bounced off the surface is called *reflected light.*

solar cell. A photovoltaic cell that is designed specifically to produce electrical energy from sunlight.

solar constant. In physics the solar constant is the rate at which energy is received from the sun at just outside the earth's atmosphere at an average distance of the earth from the sun. This is about 136 mW/cm^2.

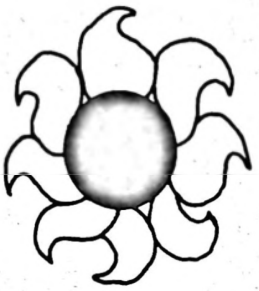
solar Energizer. A trade name of the Solarex Corporation for a solar panel.

solar panel. A collection of solar cells connected in series, in parallel, or in series-parallel combination to provide greater voltage, current, or power than can be furnished by a single solar cell. Solar panels can be provided to furnish any desired voltage, current, or power. They are made up as a complete assembly. Larger collections of solar panels are usually called solar arrays.

temperature coefficient of a solar cell. The amount by which the voltage, current, or power from a solar cell will change with changes in the temperature of the cell.

Unipanel. A trade name of the Solarex Corporation for a type of solar panel.

voltage-current characteristic. A plot of the current output of a solar cell versus its terminal voltage. Usually several curves are given for different amounts of sunlight reaching the cell.



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NEW ENERGY SCIENCES
(305) 872-3976
P. O. BOX 417
BIG PINE KEY, FL 33043

Appendix
Solarex Distributors

Solarex products are available from:

U.S.A.

Energy Sciences
(Solarex Factory Outlet)
832 Rockville Pike
Rockville, MD 20850
Telephone: (301) 279-0988

New Energy Sciences
(Solarex Factory Outlet)
Tysons Corner Regional Shopping Center
McLean, VA 22102
Telephone: (703) 448-8668

Energy Sciences
Lakeforest Mall
Gaithersburg, MD 20879
Telephone: (301) 977-3702

Solarex Ventures Group
(Wholesale consumer products, cathodic protection, navigational aids, aerospace division)
1301 Piccard Drive
Rockville, MD 20850
Telephone: (301) 948-0202

Solarex USA Western Regional Office
8141 West I-70
Frontage Road North
Arvada, CO 80002
Telephone: (303) 425-5992

Solarex USA Far West Regional Office
1220 H. Street
Suite 202
Sacramento, CA 95814

Semix, Incorporated
(manufactures silicon wafers only)
15801 Gaither Road
Gaithersburg, MD 20877
Telephone: (301) 948-4680
Telex: 64358 SOLAREX

WORLDWIDE
Solarex S.A.
Chemin de la Cretaux
Zone Industrielle Sud
P.O. Box 1196 Gland
Switzerland
Telephone: (22) 64 21 72
Telex: 28603 Solar Ch

North America: Canada
Lenbrook Industries Ltd.
1145 Bellamy Road
Scarborough
Ontario M1H1H5, Canada
Telephone: (416) 438-4610
Telex: 065-25485

France
FRANCEPHOTON
B.P. 119
Usine Des Agriers
16004 Angouleme Cedex, France
Telephone: 45/624111
Telex: 790244

Italy
SOLARIX S.p.A.
Via C Bini 44
Florence, Italy 50134
Telephone: 055/490310
Telex: 570126

Spain
Ecasol SA
Goya 39-2°
Madrid-1, Spain
Telephone: 401/4458
Telex: 23239 PCP

Switzerland and Austria
Photonetics SA
Levratte 20
Case Postale 17
CH-1260 Nyon, Switzerland
Telephone: 022/616631
Telex: 27480

Netherlands
Holecsol Systems b.v.
5600 CH Eindhoven
Holland
P.O. Box 2300
Hoevenweg 1, Netherlands
Telephone: 040/524655
Telex: 59030 HOSOL

Australia
Solarex Pty., LTD.
5 Bellona Avenue
Regents Park NSW 2143,
Australia
Telephone: 645-3131
Telex: 21975

England
Solapak Limited
Robinson House, Station Road
Columbia, District 9, Washington
Tyne and Wear, NE38 7BD
England
Telephone: 0632/471525
Telex: 537925

Solarex Ventures Group Products Catalog

SolairCool® Safari Hat

The helmet with the built-in breeze! A small solar panel powers a tiny but strong fan that blows over a water-soaked sponge, generating a cool, steady breeze. The ultimate in hot-climate comfort.
3V, 150-200 mA.
ES 602073070

How Does It Work?

The little (photovoltaic) solar cells within this protective panel provide power to the fan by changing the sun's rays into electricity!! These small cells are marvels of the latest solar technology. *Through them the sun will turn the fan—continuously!!*

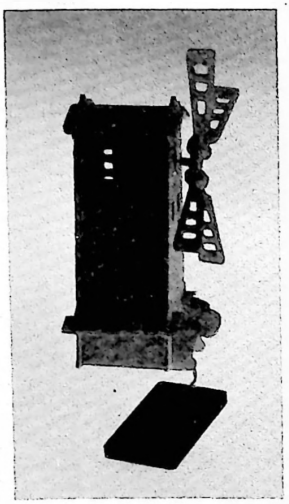
- Lightweight—8 oz.
- Unlimited solar life
- Evaporative cooling system
- Quiet operation
- Adjustable head band—one size fits all to 7½ max.
- Battery powered for indoor operation
- For all sport and outdoor enthusiasts
- Cool white color
- Open weave construction

This patented device, invented by a physician, is ideal for outdoor work, lawn-cutting, gardening, fishing, etc. SolairCool Safari Hat.

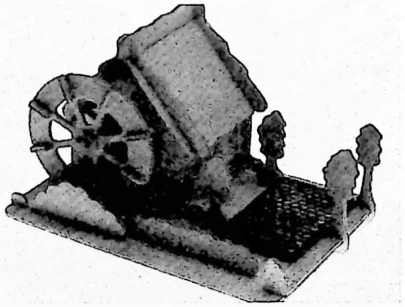
SOLAR POWERED KINETIC ARTFORMS

Solar Kinetic artforms are contemporary, handcrafted "sculptures in motion." Each unit is powered by a solar cell module. When illuminated, the module runs a small motor (approximately 0.35-1.5 Vdc), giving motion to pumps, propellors and various other mechanisms. There seems to be no limit to the imagination of these whirling, turning, spinning wonders!

Woodkits



A



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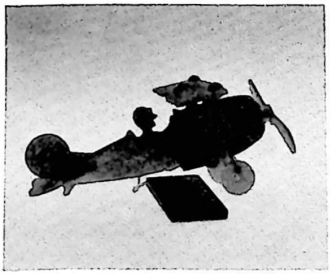

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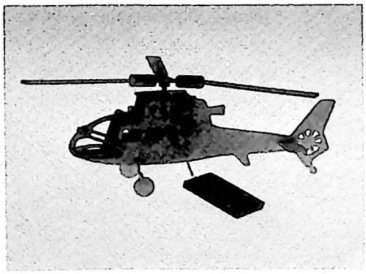


D

A. Wooden Windmill Kit
9″ × 4″ × 4″, 10 oz.
ES 253573002

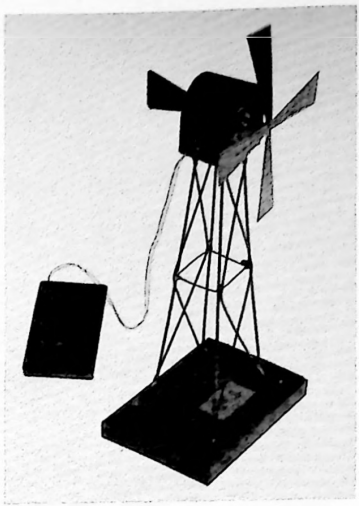
B. Wooden Watermill Kit
10¾″ × 9″ × 2″, 8 oz.
ES 253573003

C. Wooden Airplane Kit
9″ × 8″ × 4″, 9 oz.
ES 253573004

D. Wooden Helicopter Kit
12″ × 12″ × 4″, 9 oz.
ES 253573001

Copper

A. Copper Windmill
9″ × 4″ × 4″, 8 oz.
ES 253573042
B. Copper Helicopter
11½″ long, 9″ blade diameter, 9 oz.
ES 253573040
C. Copper Airplane
8″ × 8″ × 3″, 12 oz.
ES 253573041



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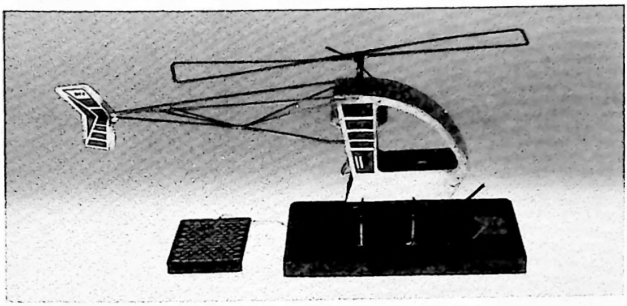

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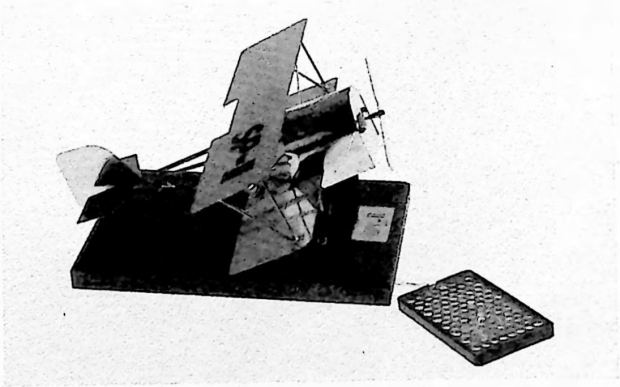

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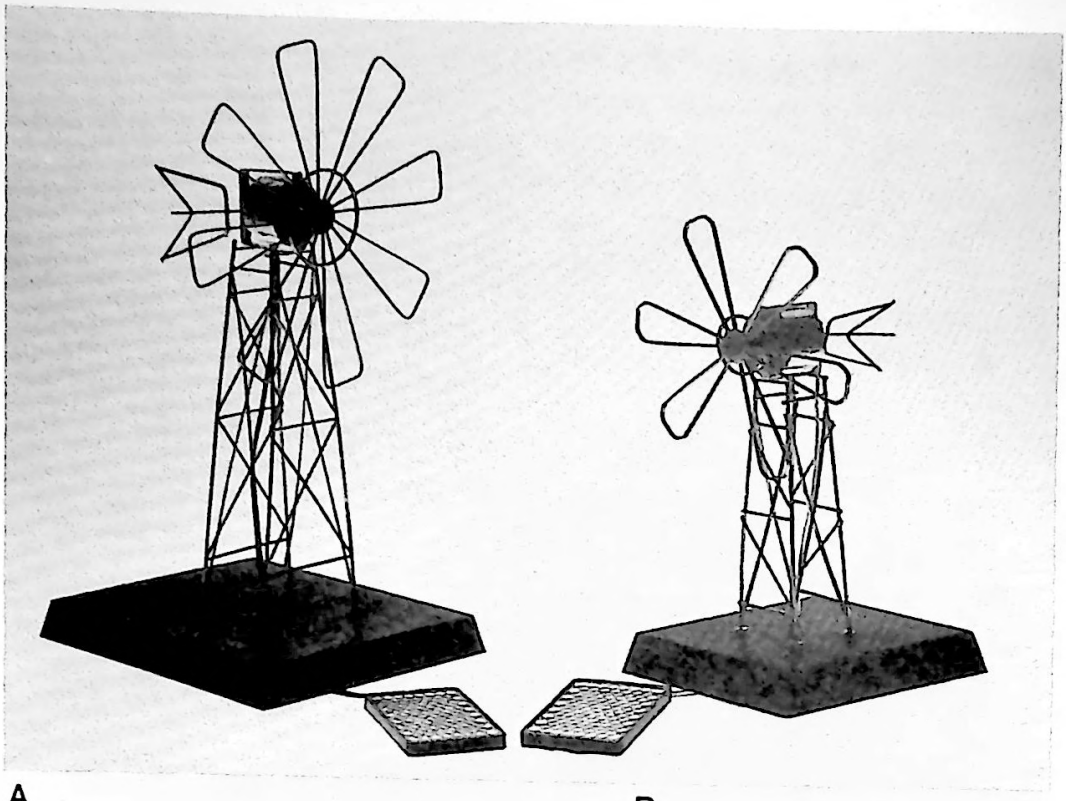

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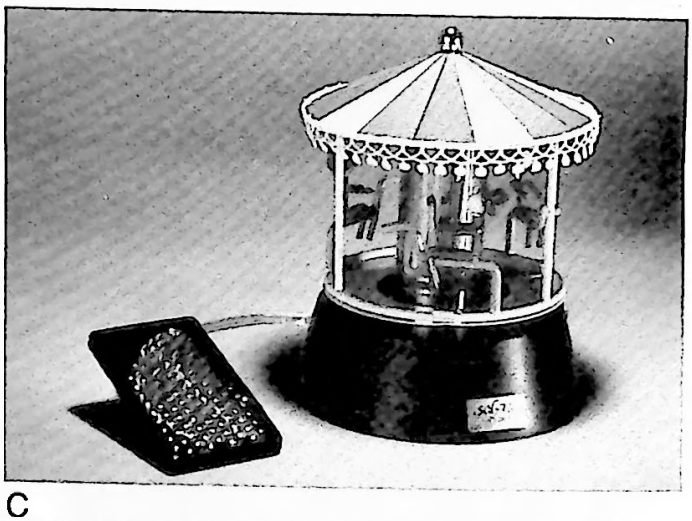

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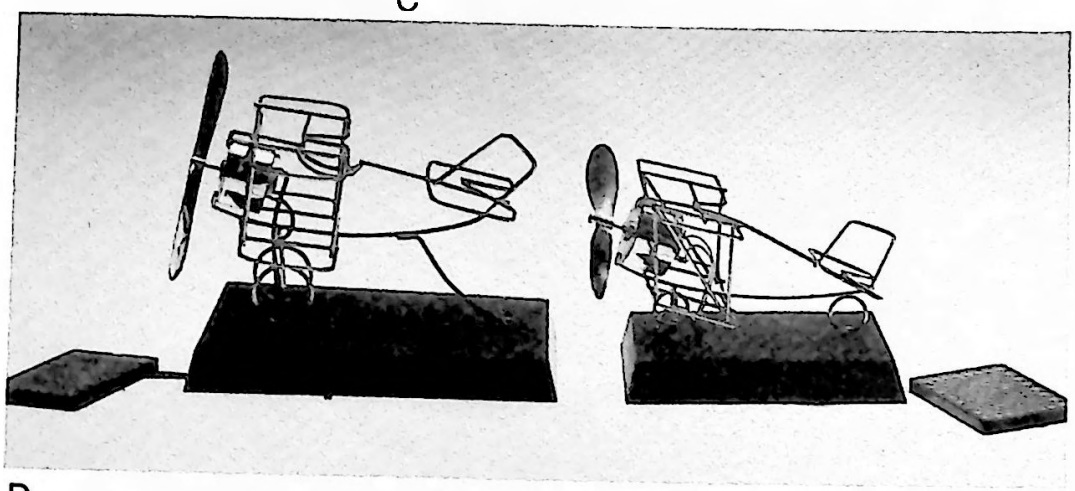

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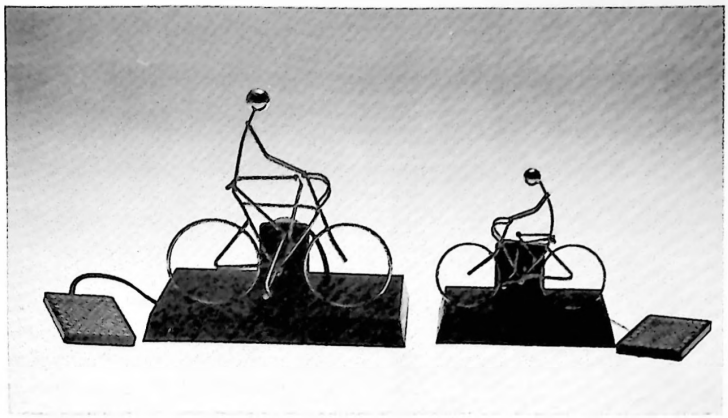

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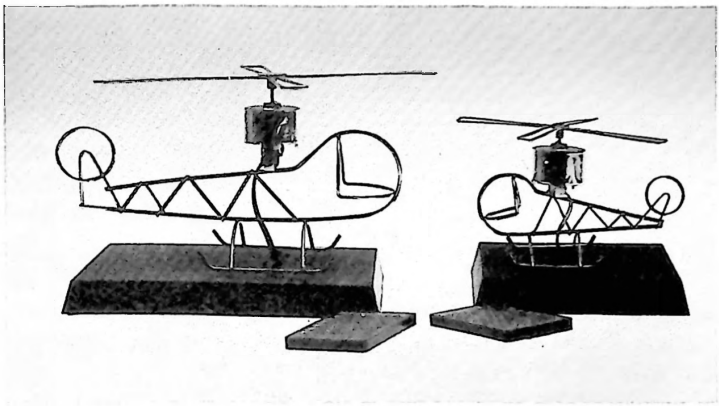


H I

A. Windmill
7″ × 9½″ × 6″, 8 oz.
ES 253573022

B. Smaller Windmill
5″ × 7″ × 4¼″, 5 oz.
ES 253573023

C. Solar Chrome Carousel (Merry-Go-Round)
4½″ diameter, 6″ tall, 15 oz.
ES 253573028

D. Biplane
7½″ × 5″ × 6½″, 8 oz.
ES 252573020

E. Smaller Biplane
6″ × 4″ × 4½″, 6 oz.
ES 253573021

F. Bicycle
7″ × 7″ × 6″, 10 oz.
ES 253573024

G. Smaller Bicycle
5″ × 5″ × 4½″, 8 oz.
ES 253573025

H. Sun-Powered Helicopter
8½″ × 5″ × 6″, 10 oz.
ES 25373026

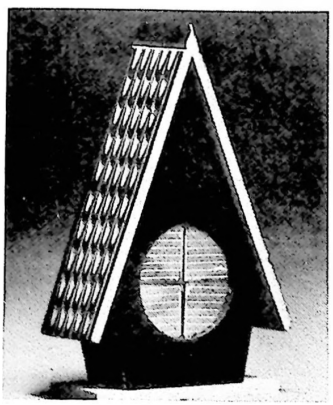
I. Smaller Helicopter
5¼″ × 4½″ × 4¼″, 6 oz.
ES 253573027

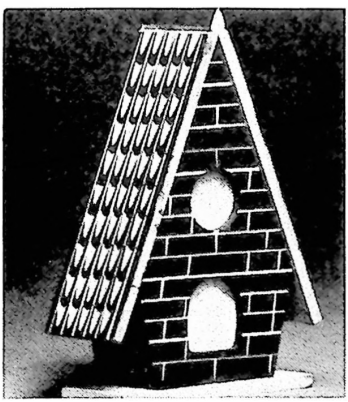
Bird Cage

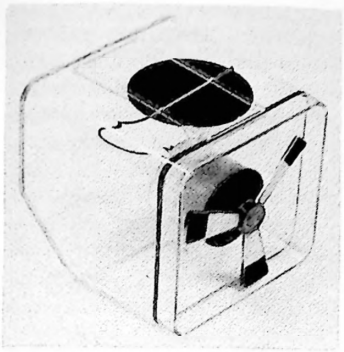
The world's only solar-operated caged bird; no muss, no fuss. An attractive brass-tone cage, measuring 4¼" × 4", with a height of 11 inches, provides a home for the fine feathered friend. Solar chips located in the floor of the cage activate a continuous chirping mechanism when exposed to available light. Put the bird to rest by turning the switch, located on one side of the base, to the off position. Packaged in an attractive display box, the unit weighs 1¾ pounds. Unpackaged, the unit weighs approximately one pound. What more can you ask of a solar-powered, carefree, feathered friend!?
ES 602073056

Birdhouse

A unique birdhouse that sings in the sunshine. Solar cells mounted on the back of the hand-crafted wooden chalet use the principle of photovoltaics to change sunlight directly into electricity and power and solid state circuitry that provides the bird song. The birdhouse measures 7½" height by 2¼" width and weighs 8 ounces.
ES 602073050







Fan Cube

Attractive, four-inch plastic cube has silicon solar cell mounted on the top which converts sunlight to electricity, causing the propeller on the cube to spin. Cube is angled to allow maximum exposure to sun. Intensity of sunlight causes propeller to spin fast or slow. Also available in kit form.

ES 602073000

Fan Cube Kit

ES 602073010

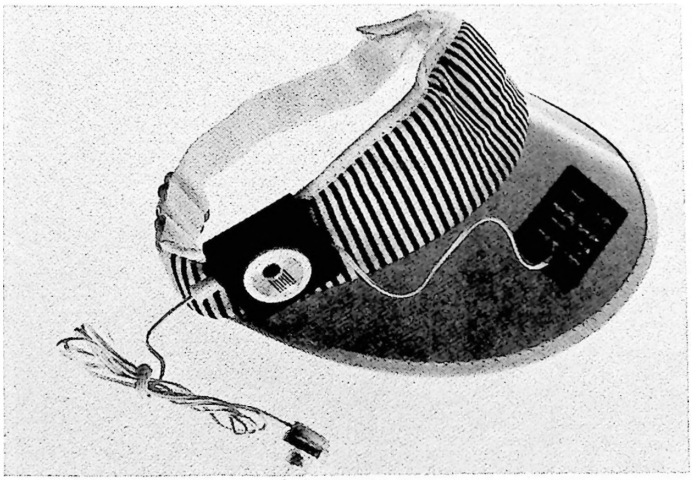
Hat Visor AM Radio

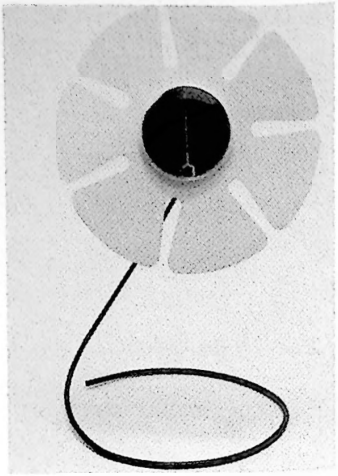
The Hat Visor AM radio set comes complete with an attractive blue and white visor, which is flexible and washable when detached from the radio. The radio and the panel are detachable, so you can attach the radio to any visor or object you wish. Two pairs of hook and loop tapes are supplied in order to obtain maximum sunlight and comfort by selecting position ing. Included is an ear plug on two-foot cord which, when plu ged into the side of the radio, pr vides many hours of private listen ing enjoyment.

ES 602073024

Clip-on Visor Radio (without visor)

ES 602073025



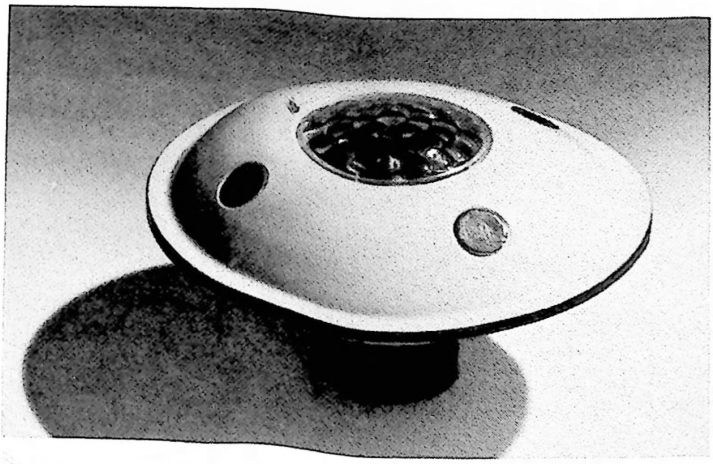


Solar Sunflower

Bright, nine-inch yellow sunflower spins gaily in the sunshine. The three-inch silicon solar cell powers a small electric motor by changing sunlight into electricity.
ES 602073054

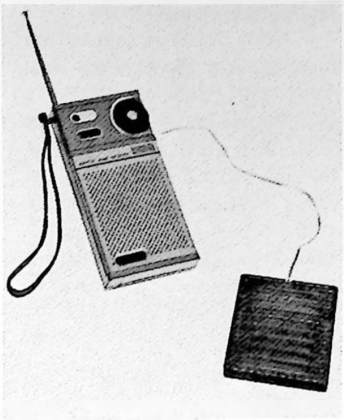
UFO II

Solarex presents its very own solar-powered spaceship, the UFO II. The bright yellow UFO II is five inches in diameter, three inches in height, and weighs approximately ¼ pound. Located in the center top, protected by a clear acrylic bubble, is a solar cell. When exposed to direct sunlight or incandescent light, the cell activates the inner motor, causing the UFO II to spin. To cease the spinning motion, simply remove the UFO II from the light source, and store away until the next desired flight.
ES 602073055



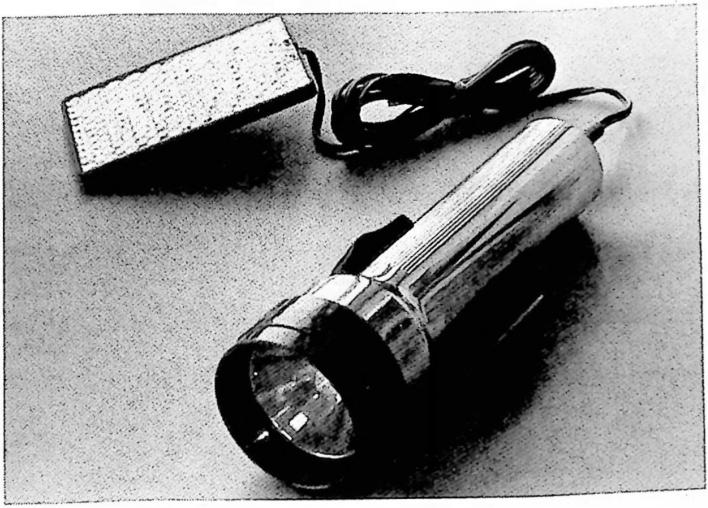
AM/FM Pocket Radio

Ten rectangular solar cells, connected in series, are mounted in a sturdy 3½" × 2¼" blue plastic case. The panel includes 20 inches of cord and a mini-radio. Under full sun the panel will produce 4.5 volts@80 ma, to power the radio directly, or recharge two AA Nicad™ batteries. Using the batteries, you can continue to listen to your favorite station indoors, or anywhere after the sun goes down. When necessary, the batteries may be recharged by turning the radio off, connecting the panel, and placing the panel in full sunlight.
ES 602073027



Solar Flashlight

Practical demonstrator of solar electric power—a rechargeable flashlight. Mini-array panel recharges two rechargeable batteries. To use, simply unplug array from base and use as any other flashlight. Flashlight features magnetic clamp for easy storage and sturdy metal body for long life. Array is attached by 68" charging leads. Rechargeable batteries included. 7½" long, 12 oz.
ES 602073007



Mechanical Musical Piano

Enjoy the sunny tunes of the Solarex Solar Piano Music Box. An attractive item in the form of a Baby Grand Piano, the body consists of a clear acrylic plastic through which the solar cells and inner musical movements are visible. Resting on three gold-tone legs, the piano sports a realistic white keyboard with black keys. Three pieces of silicon solar cells are mounted on top of the piano body. When exposed to direct sunlight or a high intensity (100 watt) light bulb, the music mechanism becomes activated by solar power, and the musical tune continues until the piano is removed from the light source.

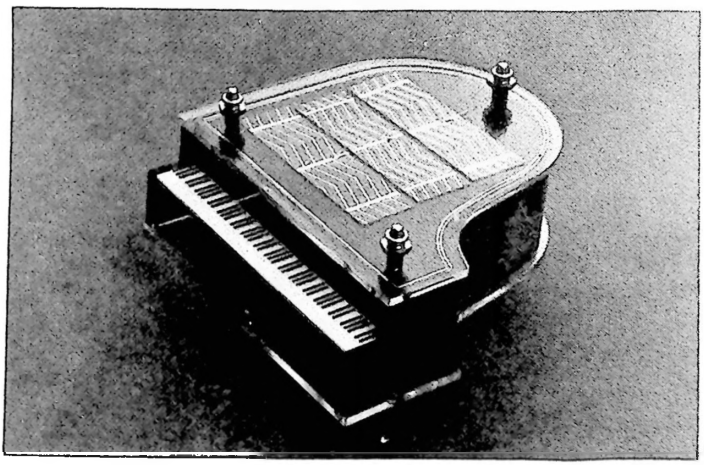
This "Grand" piano weighs only half a pound and measures 4¾" × 4¼". A delightful gift to give or receive, the solar piano is a unique collector's item or conversation piece.

ES 602073026—"Love Story"
ES 602073060—"It's a Small World"
ES 602073061—"Lullaby"
ES 602073062—"Anchors Aweigh"
ES 602073063—"Around the World in 80 Days"
ES 602073064—"My Favorite Things"
ES 602073065—"Deck the Halls"
ES 602073066—"Edelweiss"
ES 602073067—"What Child Is This?"
ES 602073068—"I'd Like to Teach the World to Sing"
ES 602073069—"Colonel Bogey March"

Electronic Musical Piano

Featuring an integrated circuit chip, this piano plays two electronic "Switched-on Beethoven" themes when the solar cells are illuminated. A slide switch provides song selection and "off" position. Music is played through miniature speaker mounted inside piano. Looks the same as Piano Music Box pictured.

ES 602073057

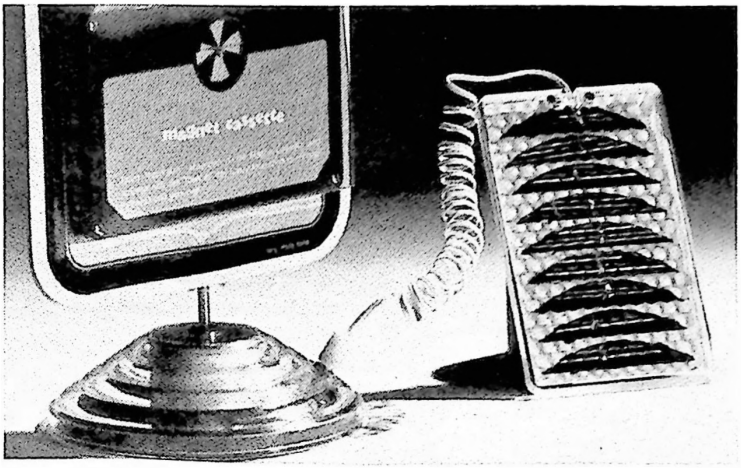


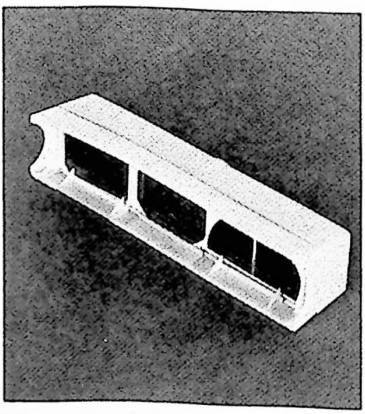
SOLAR POINT OF PURCHASE ITEMS

Solar Spinner

The Solar Spinner has solar cells mounted in its 3.5 inch wide, 1.5 inch high base which convert light directly into electricity and power a small electric motor mounted inside the base. The motor will spin a pound of materials mounted or attached to the 4.5 inch shaft at the top of the spinner.

Solar Spinner
ES 602073052
Remote Solar Spinner
ES 602073053





Fluorescent P.O.P.

Designed to be clipped onto a standard fluorescent P.O.P. revolves signs, mobiles, or any lightweight point of purchase item. The white plastic unit measures 4½" high from the top of the clips to the bottom of the hooks, is 7" long and 2½" wide. Solar cells located in the top of the unit activate the inner motor, when directly exposed to fluorescent light. On the base of the unit are two hooks, one rotates slowly, the other fast. Packaged in a plain white box, the unit weighs approxmately ½ pound.

ES 602073028

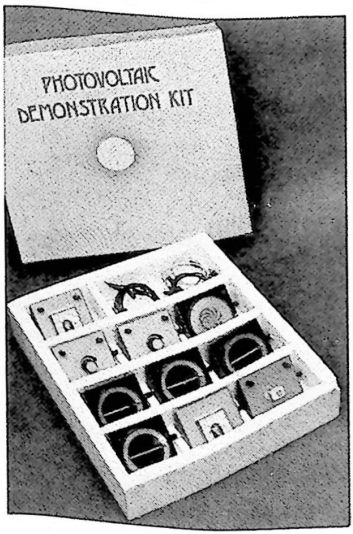
Turntable

Solarex presents a new point of purchase display item, the Solar Turntable. Weighing less than a pound, the turntable measures 6½ × 6½ inches with a height of 2⅞ inches. A 1¾ × ⅞ inch mini panel is attached to the side of the attractive light brown wood grain housing. When exposed to direct sunlight, or incandescent light, the solar chip provides approximately .45 volts@ 60-80 ma to activate the mini motor. The speed at which the four inch round diameter turntable rotates is determined by the intensity of the available light. Designed to support up to 10 pounds, the turntable is a delightful way to display any item, or rotate a plant to ensure even sunlight.
ES 602073021

EDUCATIONAL MATERIALS

Photovoltaic Demo. Kit

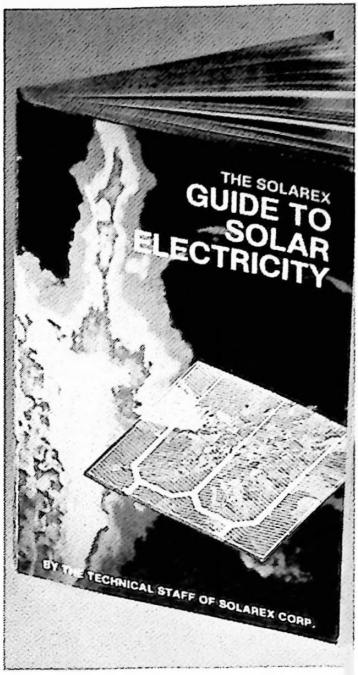
The most elaborate and complete kit on photovoltaics. Includes 19 component parts that can be interconnected to provide literally hundreds of different circuits, either series or parallel. Individual modules measure 3½" × 2½" × 2½". Housings are made of aluminum with plastic shields to protect fragile solar cells. Expanded foam packaging minimizes breakage possibilities in transit and storage against friction, jamming pressure or impact.
ES 602073005



Solarex Guide to Solar Electricity

Nine clear, concise chapters cover everything from a glossary of solar electric terms, how to use cells and practical solar electric generators, to the rapidly exploding variety of industrial, educational, consumer, and military applications. It also includes solar electric projects, commercially available accessories, the use of solar cells as light sensors rather than as power sources, and much, much more.

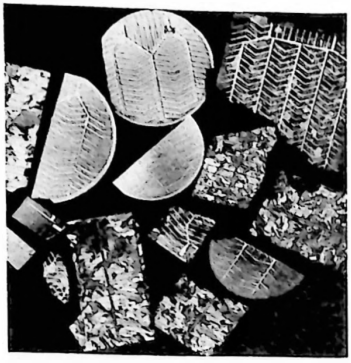
ES 602073006



Solar Energy Kit

This photovoltaic Solar Energy Kit is designed for use by all individuals who are curious about solar energy. Included in the kit is a booklet containing general information on solar energy, and a solar cell, which is encapsulated in a 1¾" × 2⅞" panel. Also included is a 1.5 volt dc motor, a red plastic propeller, and one 12 inch lead wire. Packaged in a 6½" × 8¾" hang tab display package, the unit is very popular in hobby shops, electronic outlets, and novelty stores. A fun way to acquire basic knowledge about the energy source of the future!

ES 602073003



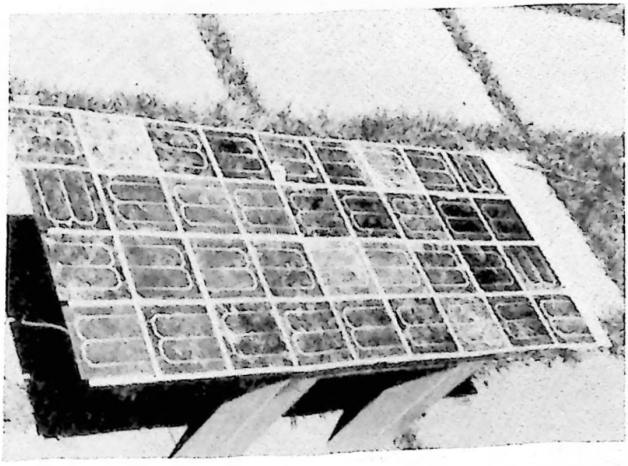
SOLAR CELL GRAB BAG

A two- to three-ounce bag of first grade solar cells broken or cracked in manufacture. Irregular sizes and shapes. Approximate size 1 cm to 4 cm in width, length, or diameter. Outputs vary from 50 to several hundred milliamps. Can be soldered in series or parallel for greater voltage or current. Great for hobbies, crafts, experiments, and school projects.
ES 602173015

"Build Your Own Solar Electric Panel" Kit

Build your own photovoltaic panel with our new Solar Electric Panel Kit. Aluminum frame measures 17¼" × 38½" × ½". Frame accommodates thirty-six 10×10 cm solar cells. Cells strung in series produce between 1.2-1.5 amps at 12 volts; in parallel, they produce 2.4-3.0 amps at 6 volts. Kit includes 36 solar cells. Sunadex solar glass, white aluminum frame, tabbing material, and two color-coded 6" terminal wires. You provide silicone potting. Ideal for do-it-yourselfers, demonstrators, and educators. Panels can be constructed in less than two hours soldering time each. Instructions included, but it is recommended you have basic soldering skills.

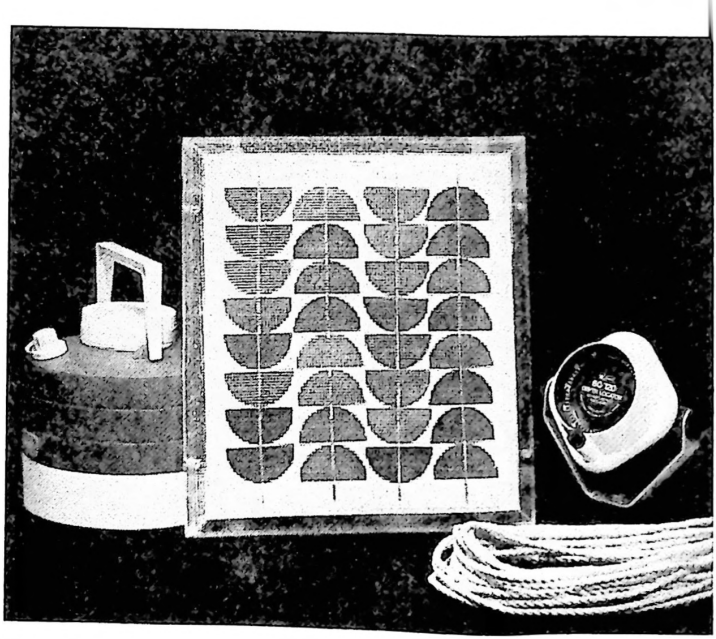
ES 454073040



MARINE AND RECREATIONAL PANELS

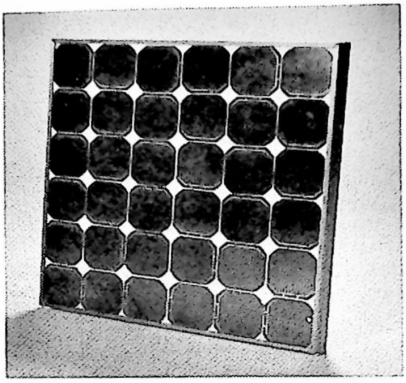
1270M Marine Panel

The 1270M Solar Energizer®, a 9 watt (peak), 12 volt D.C. Photovoltaic panel, provides sailboats and yachts with an auxiliary generator with an inexhaustible free fuel supply. Since the 1270M is capable of maintaining a fully charged typical marine battery, it can, for example, remove an average of 2,000 gallons of bilge water per week, power an FM or CB transceiver, or operate navigational lights. The panel uses 32 series connected, half 3" diameter silicon solar cells to convert sunlight directly into electricity. The cells are encapsulated in an ultraviolet stabilized silicone rubber housed in a corrosion-proof, virtually indestructible acrylic plastic with a reinforced polyester backing. A separate in-line blocking diode prevents reverse current (discharge) flow through the battery during darkness. Measuring 15" × 14" and weighing approximately 7 pounds, the 1270M will typically produce 600 ma at 12 Vdc nominal in full sunlight. The recessed stainless steel threaded inserts and 20 ft. long AWG #18 gauge insulated leads, provide quick and easy installation of the 1270M on any relatively flat surface.
ES 454072070



HE51M Marine Panel

The Solarex HE51M is a high density photovoltaic panel, rated at 34 watts (peak) and 2.1 amps at 14 volts nominal. Measuring approximately 23" × 23", the 33.5 pound panel consists of 36 encapsulated solar cells, a stainless steel frame, and a corrosion-resistant junction box. Designed for use in marine applications, the open-circuit voltage is 20.5 Current (A)@nominal voltage is 2.1, and the weekly ampere hours are 63.0.
ES 454072051



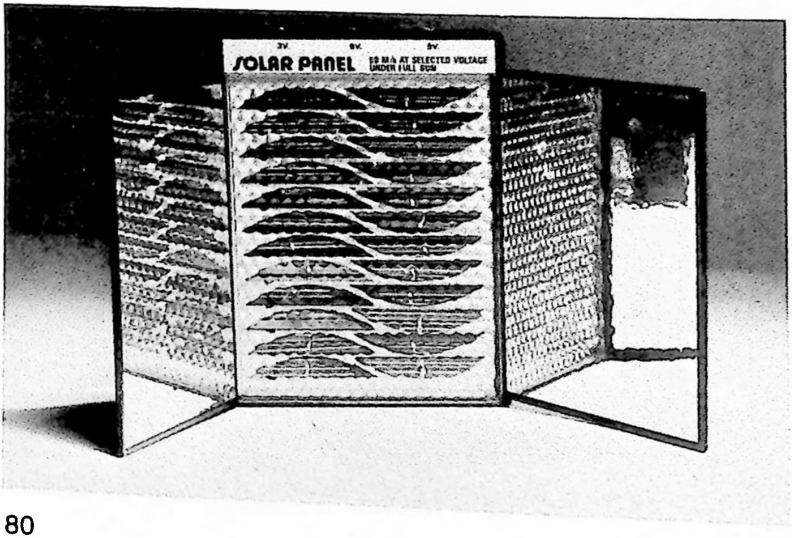
HOBBY/INDOOR PANELS

50 ma Multivolt Panel

Produces 3, 6, 9 volt power to run calculator, radio, etc. Array measures 4½" × 5¾" and comes complete with reflector panels to maximize sunlight collection/ panel output.
ES 602073017

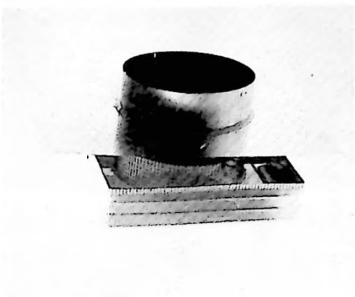
Individual Power Panels

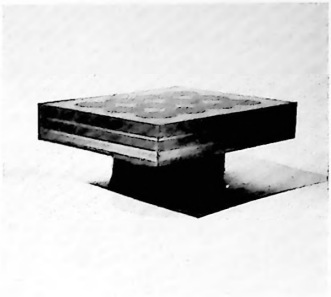
6 Vdc—50ma minipanel
ES 602073015
9 Vdc—50ma minipanel
ES 602073016
12 Vdc—50ma minipanel
ES 602073019

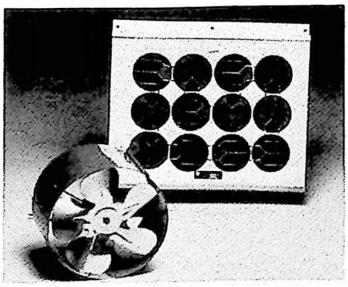


One-piece Solar Vent Fan

Easier installation with no wiring needed for fully automatic operation.
ES 602073001





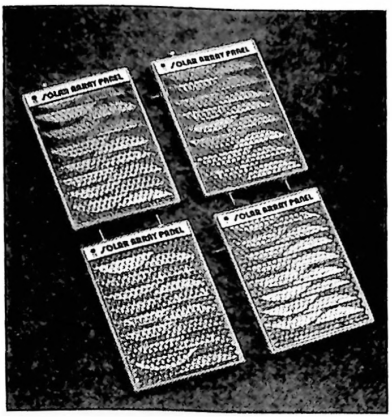


Solarvent Fan

Perfect ventilating fan for grain storage and livestock buildings, solar heating systems, attics, rest stops, and greenhouses. The eight pound, 15″ × 12″ solar panel generates over six watts in full sun. Enough output is provided to power the fan when only 15% of full sun is available. The stainless steel, five blade, 8½″ diameter fan, moves up to 350 cubic feet per minute. Vent Fan and Solar Panel are packaged as a unit, complete with installation instructions. Total shipping weight is 10 pounds.
ES 602273000

6 Vdc Array Panel

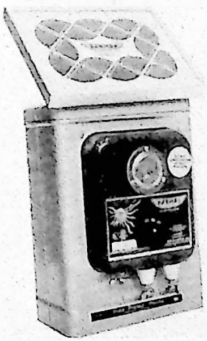
The latest in the Solarex line of indoor hobby panels, the 6 Volt Array Panel is designed with the capability of being connected in series or parallel to additional 6 Volt Array Panels. Silicon solar cells connected in series are mounted in a 4½" × 5¾" plastic case. Two interconnects are located on the bottom of the panel, and two more on the side of the panel. When exposed to incandescent or natural light, each individual panel provides 6 volts at 50 milliamps. Configurations etched onto the back of each panel provide instructions for interconnection of two panels, to provide 12 volts at 50ma, or 6 volts at 100ma.



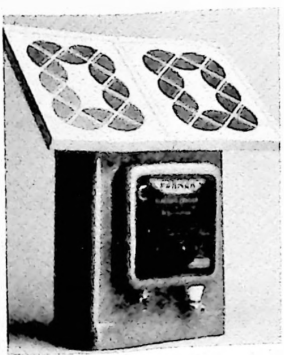
Connection of four individual panels will provide 12 volts at 100ma, or 6 volts at 200ma.
ES 602073018

Solar Fence Charger

SolarPak eliminates the need for expensive battery replacement, as the Solarex 7¼" × 9¼" panel recharges the battery. Designed to operate for 21 days in total darkness, the weatherproof unit comes complete with a sealed 6 volt gel battery. Measuring 9" × 12", the unit provides power line convenience in a battery fencer. Shipping weight is approximately 18 pounds.
ES 602272001
ES 602272002



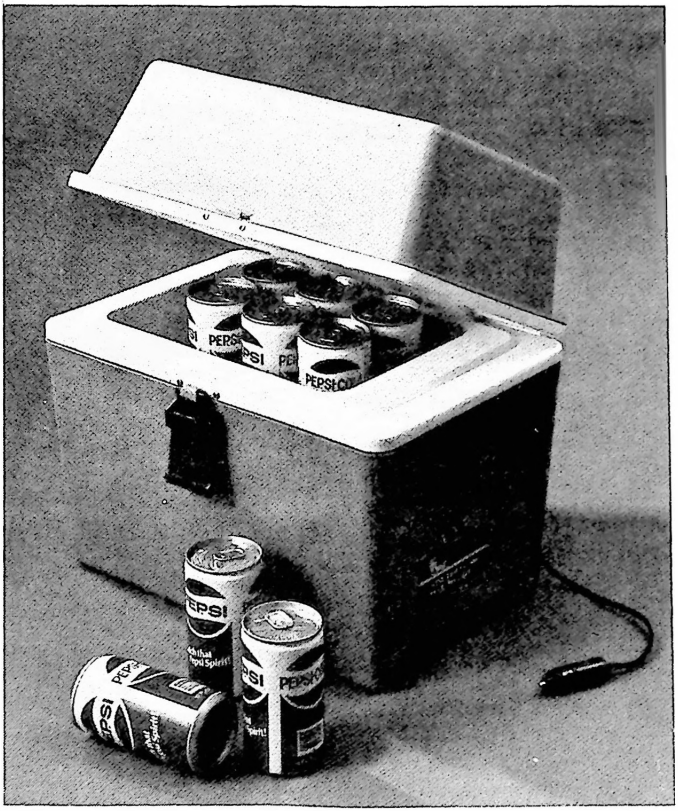
6 volt
ES 602272001



12 volt
ES 602272002

Mini Refrigerator and Food Warmer

This attractive blue mini refrigerator is 15½" high, weighs 10½ pounds and measures 16" × 11½". The refrigerator can be carried about with ease, via use of a handle located on top of the unit. Requiring 12 volts dc and an average of 2+ amps., the unit includes a power cord which fits a car, boat, van, or RV cigarette lighter socket. Once connected to the power source, the use of a switch provides selection of "hot" or "cold" temperatures. A light emitting diode will illuminate as verification that adequate power is reaching the unit. The cooling performance is approximately the same as a household refrigerator. The heating element is designed to keep hot food "hot," not to heat cold food. Once the unit has been turned off, cold food will stay cold, and hot food will stay hot, for several hours.
ES 537473035



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120 Experiment Kit	ES 602073004	29.95
Kit: "Build Your Own Solar Panel"	ES 454073040	199.00
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